

# Chandra Observations of the Galactic Center Region

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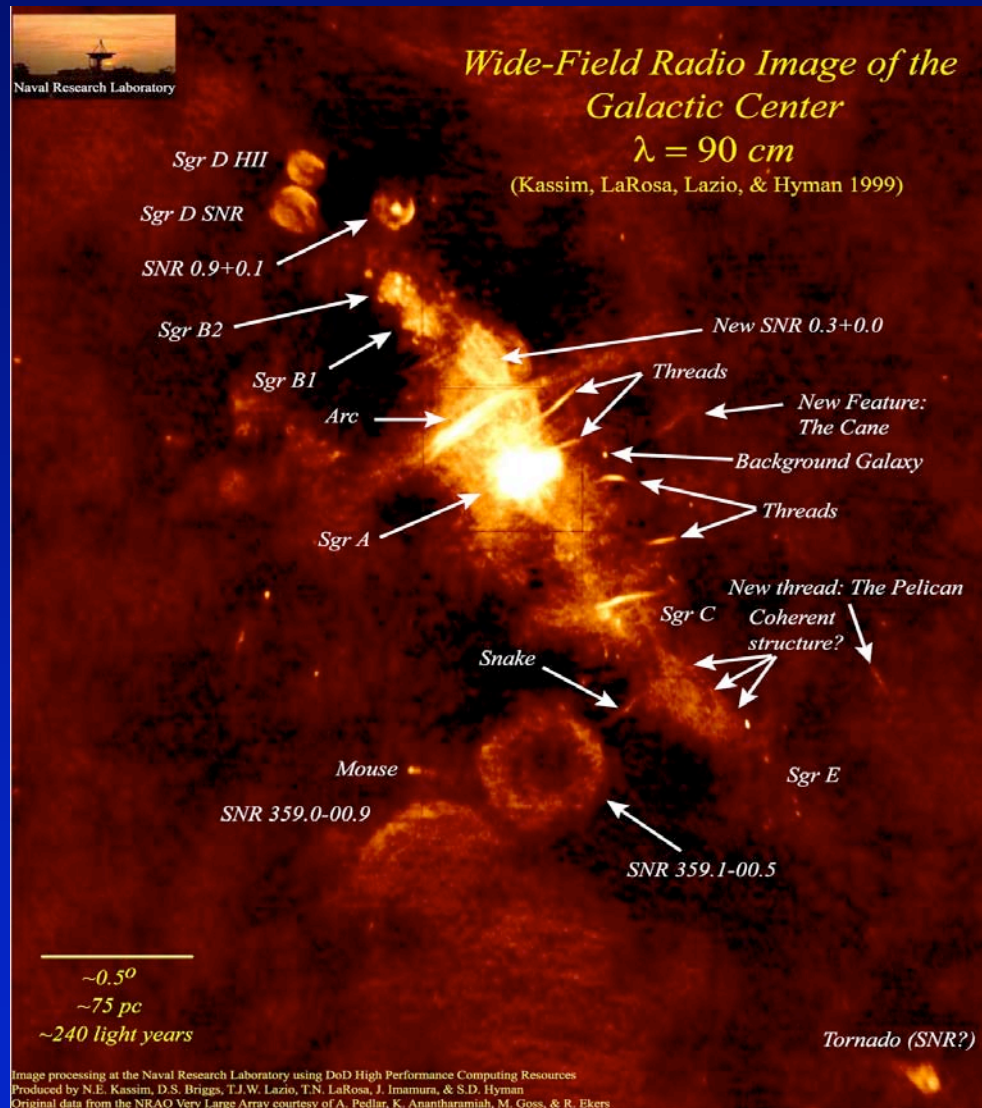
## ISAS

Yoshitomo Maeda

## Research Issues

- Supermassive black hole at the Galactic Center: Sagittarius A\*
  - Accretion physics
  - Emission mechanism of rapid X-ray/IR flares
  - Origin of the extended quiescent emission
  - Evidence for a bipolar outflow
  - Evidence for a possible X-ray jet
- Star formation history in the Nuclear Bulge
- Supernova Remnants
- Colliding stellar winds and other interactions
- Origin of new X-ray structures in the field
- Search for X-ray Pulsars
- Nature of "point-like" TeV source in central 1' of the Galaxy

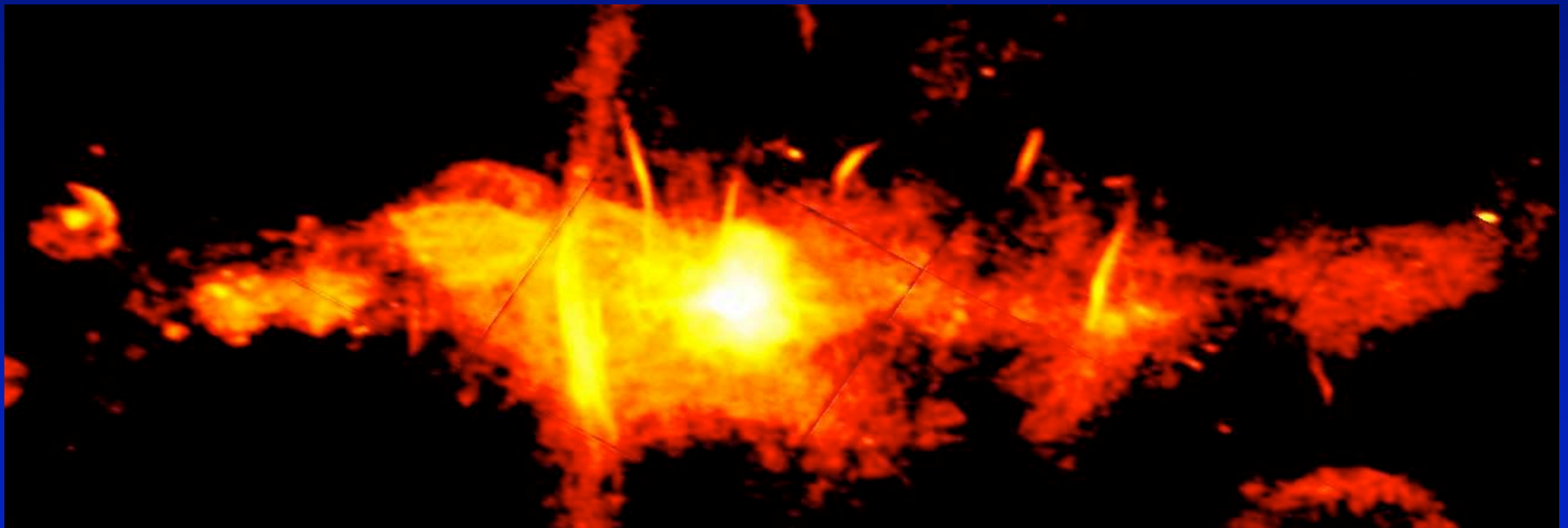
# Annotated Radio View of the Galactic Center



Credit: Kassim, LaRosa, Lazio, & Hyman

# Radio View of the Galactic Center

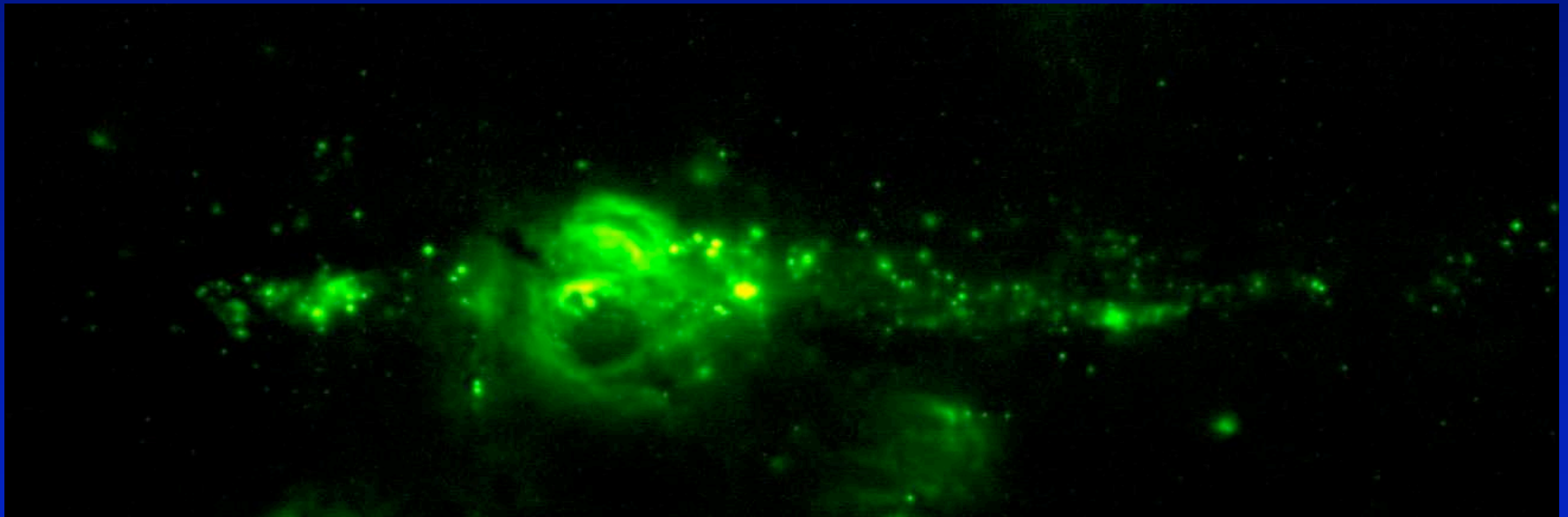
(In Galactic Coordinate System)



2 x 0.8 degrees

Credit: NRAO/VLA

## Mid-Infrared View of the Galactic Center



2 x 0.8 degrees

Credit: NASA/MSX

# Chandra Mosaic of the Nuclear Bulge

Wang, Gotthelf, and Lang (2002)

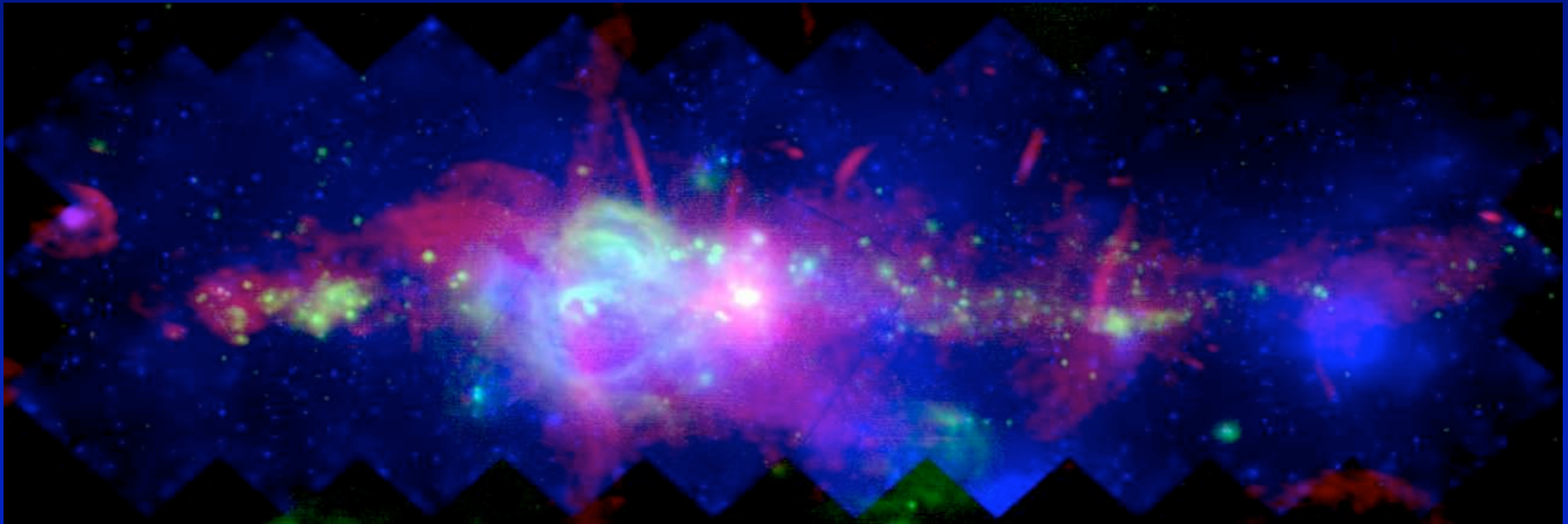


2 x 0.8 degrees

30 pc



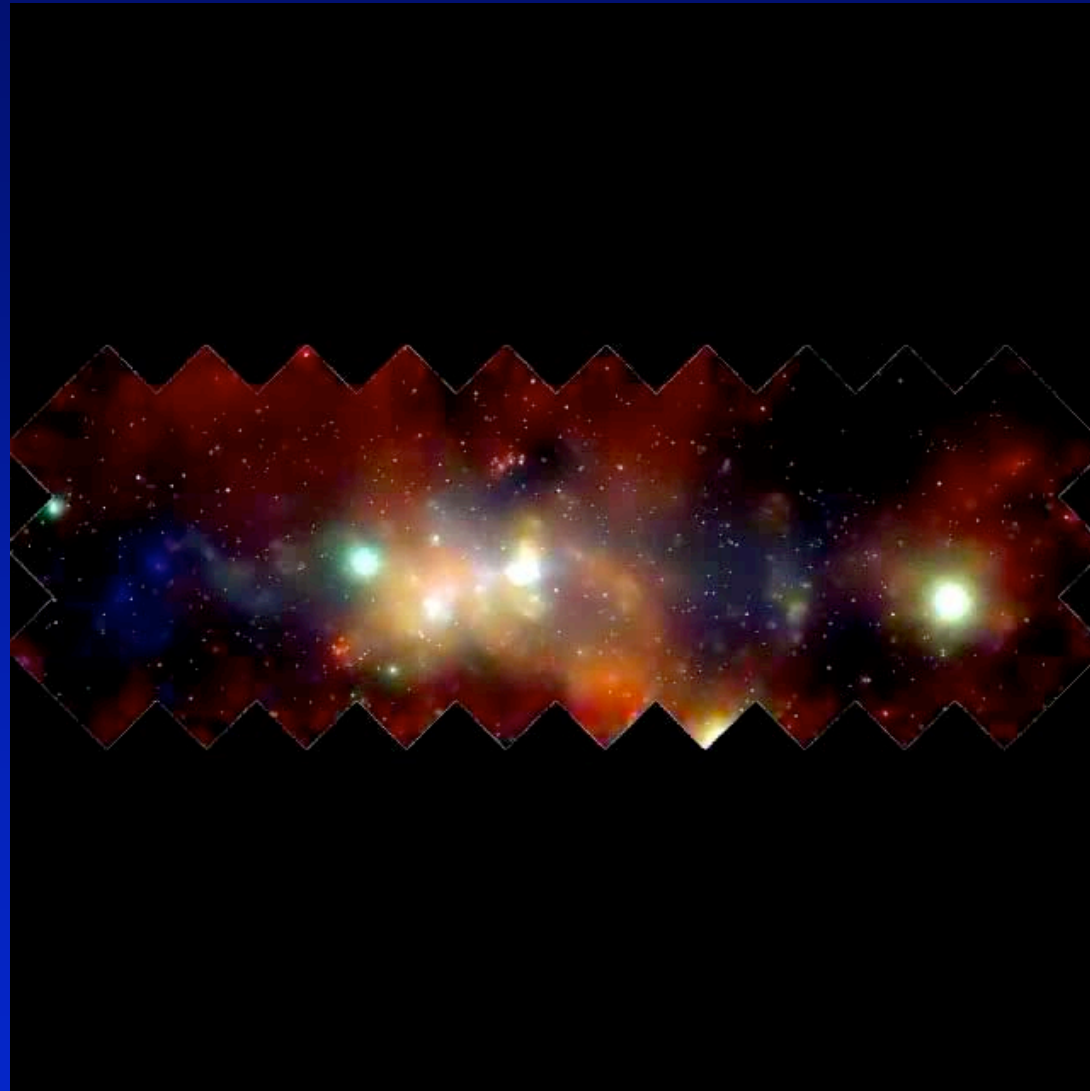
# Radio/Mid-Infrared/X-ray View of the Galactic Center



2 x 0.8 degrees

Credit: (X-ray) NASA/UMass/D. Wang et al., (Mid-IR) NASA/MSX, (Radio) NRAO/VLA

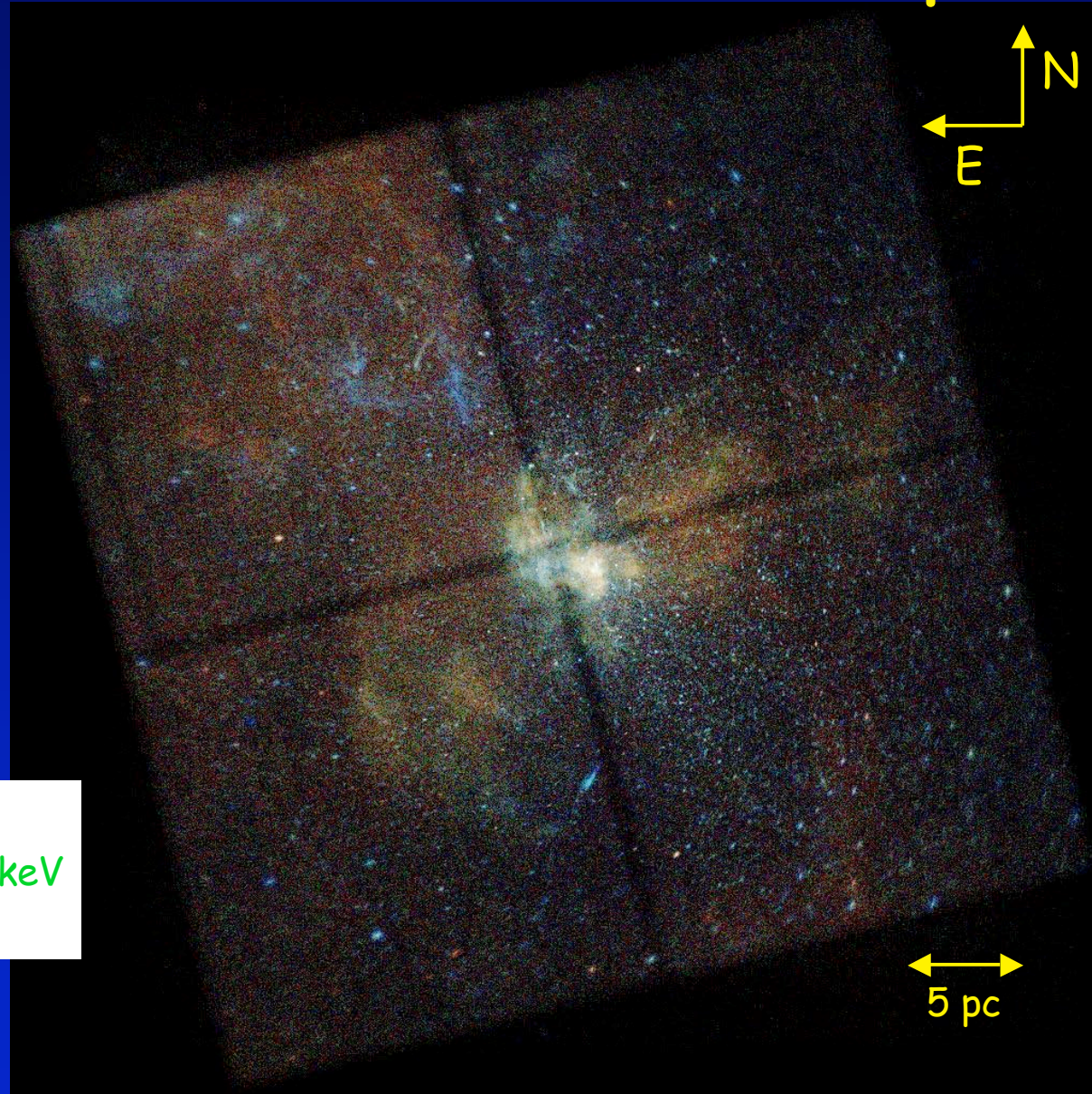
## Zooming into the Galactic Center in X-rays



Animation Credit: NASA/CXC/SAO



# Chandra Galactic Center Deep Field



17 x 17 arcmin

40 x 40 pc

590 ks

Red: 2-3.7 keV  
Green: 3.7-4.5 keV  
Blue: 4.5-8 keV

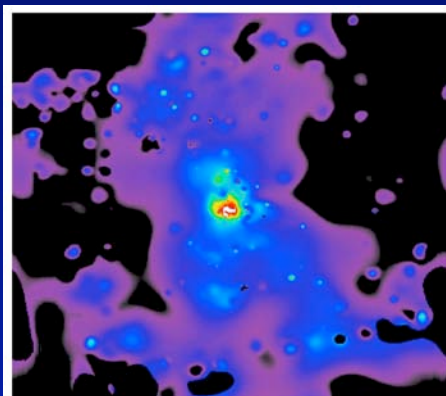
5 pc

# X-ray Emission-Line Equivalent-Width Maps

Park et al. 2004

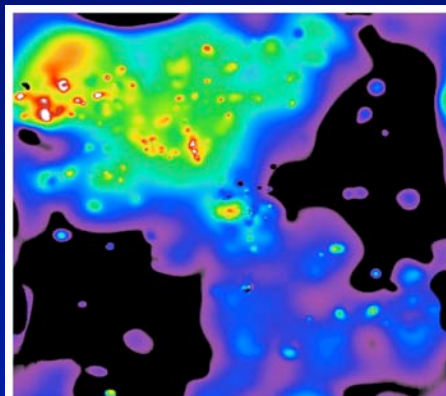
**Fe He $\alpha$**

**(E ~ 6.7 keV)**



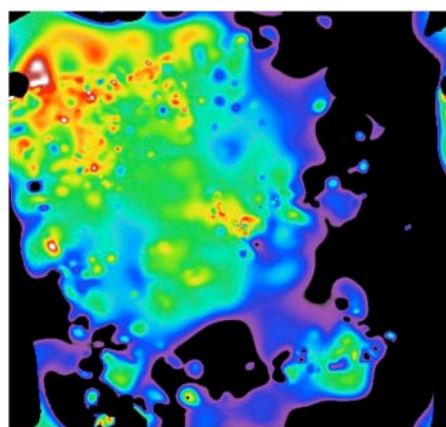
**Fe K $\alpha$  “neutral”**

**(E ~ 6.4 keV)**



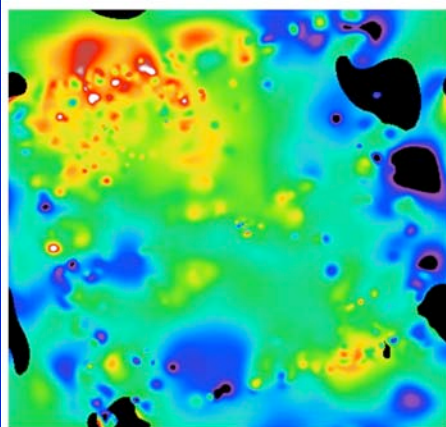
**S He $\alpha$  + Ly $\alpha$**

**(E ~ 2.5 keV)**



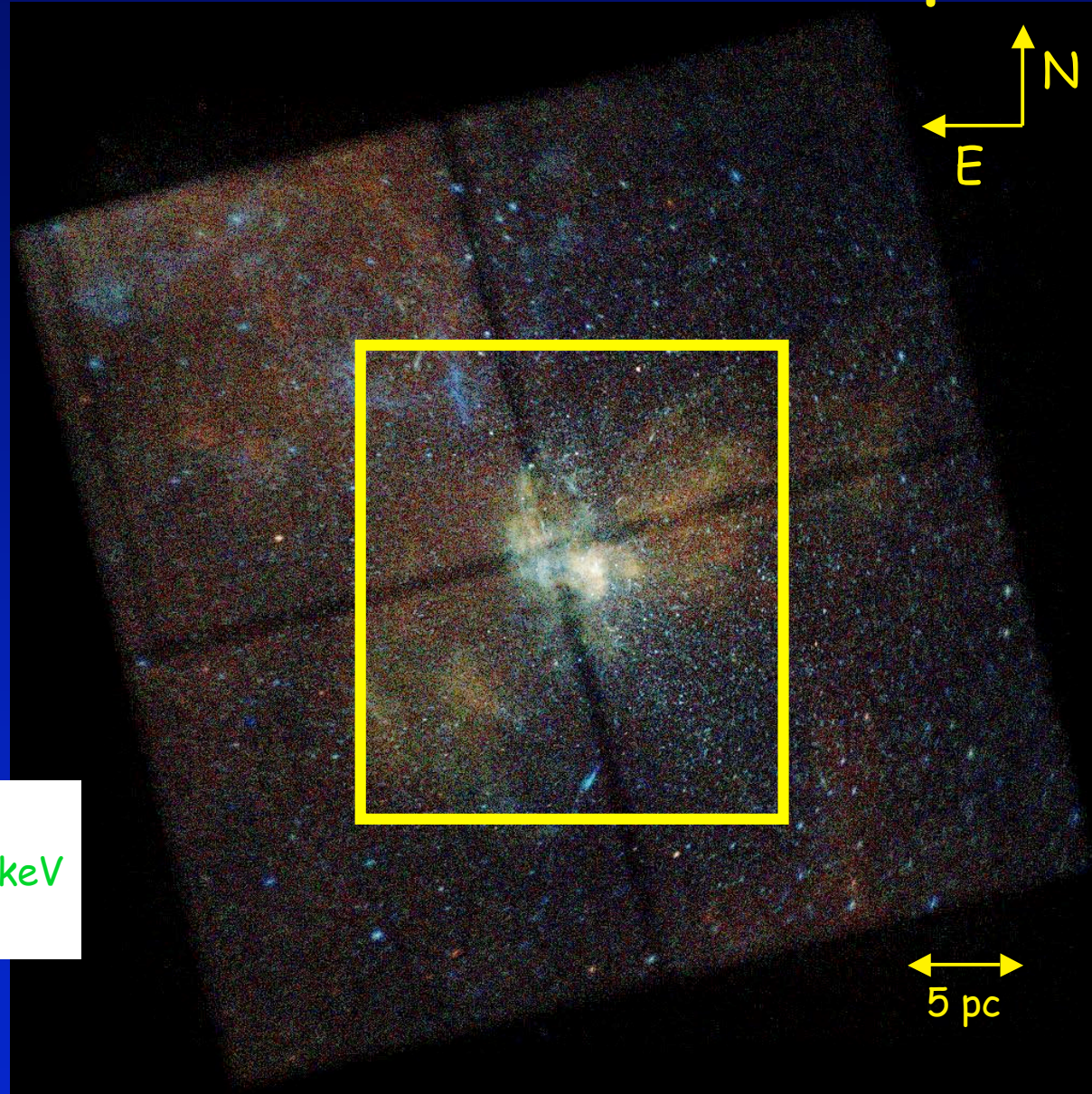
**Si He $\alpha$**

**(E ~ 1.8 keV)**





# Chandra Galactic Center Deep Field



17 x 17 arcmin

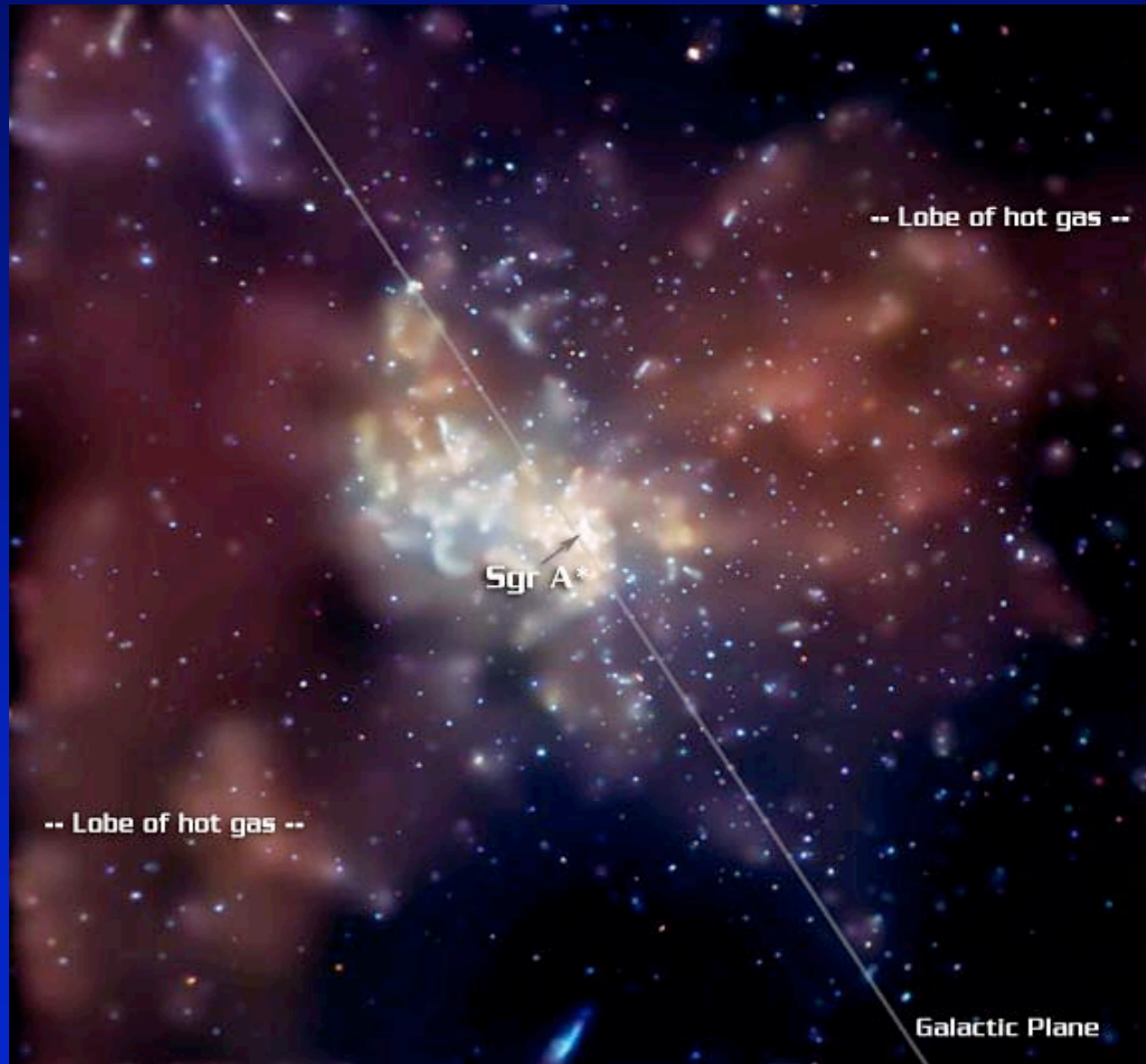
40 x 40 pc

590 ks

Red: 2-3.7 keV  
Green: 3.7-4.5 keV  
Blue: 4.5-8 keV

5 pc

# Chandra Galactic Center Deep Field

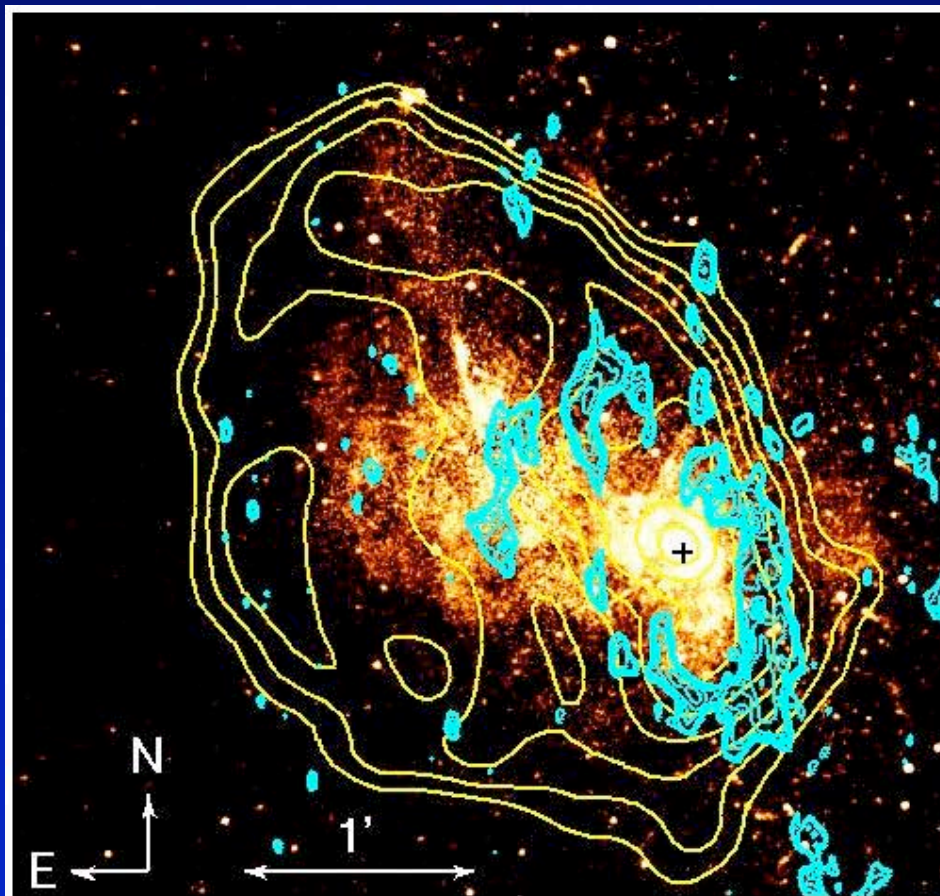


8.4 × 8.4 arcmin



## 20 cm (yellow) and HCN (blue) Contours

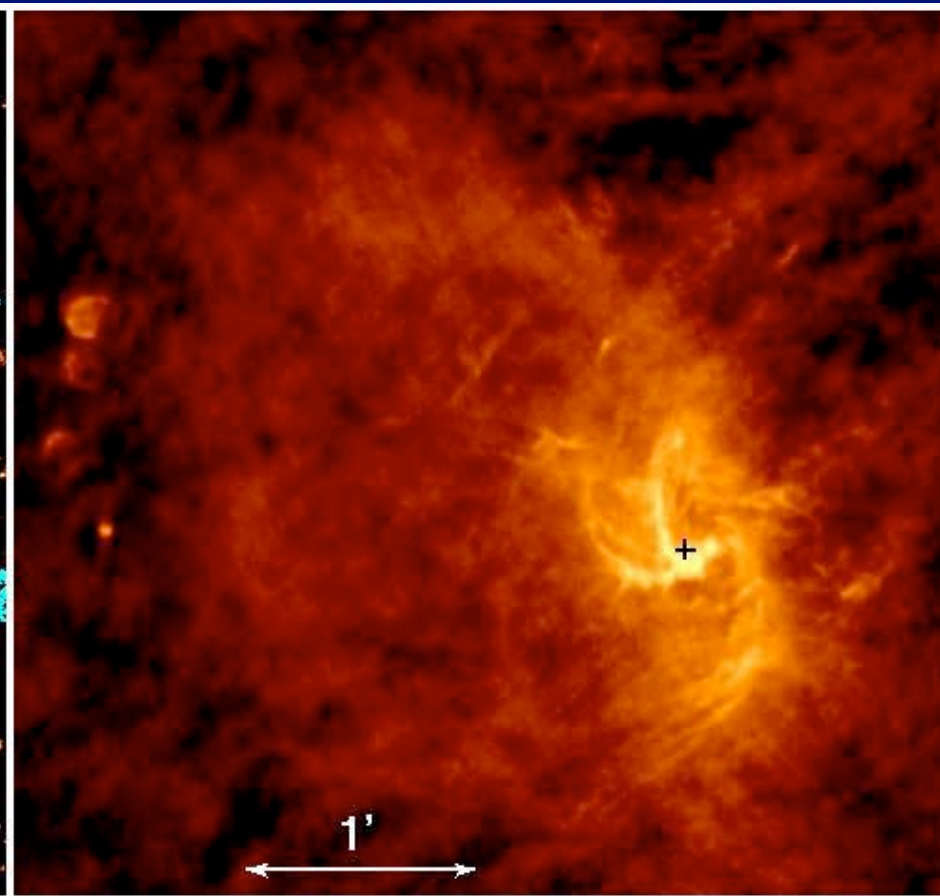
Chandra 0.5-8 keV Image



HCN: Christopher et al. 2005

X-ray: Baganoff et al.

VLA 6 cm Image

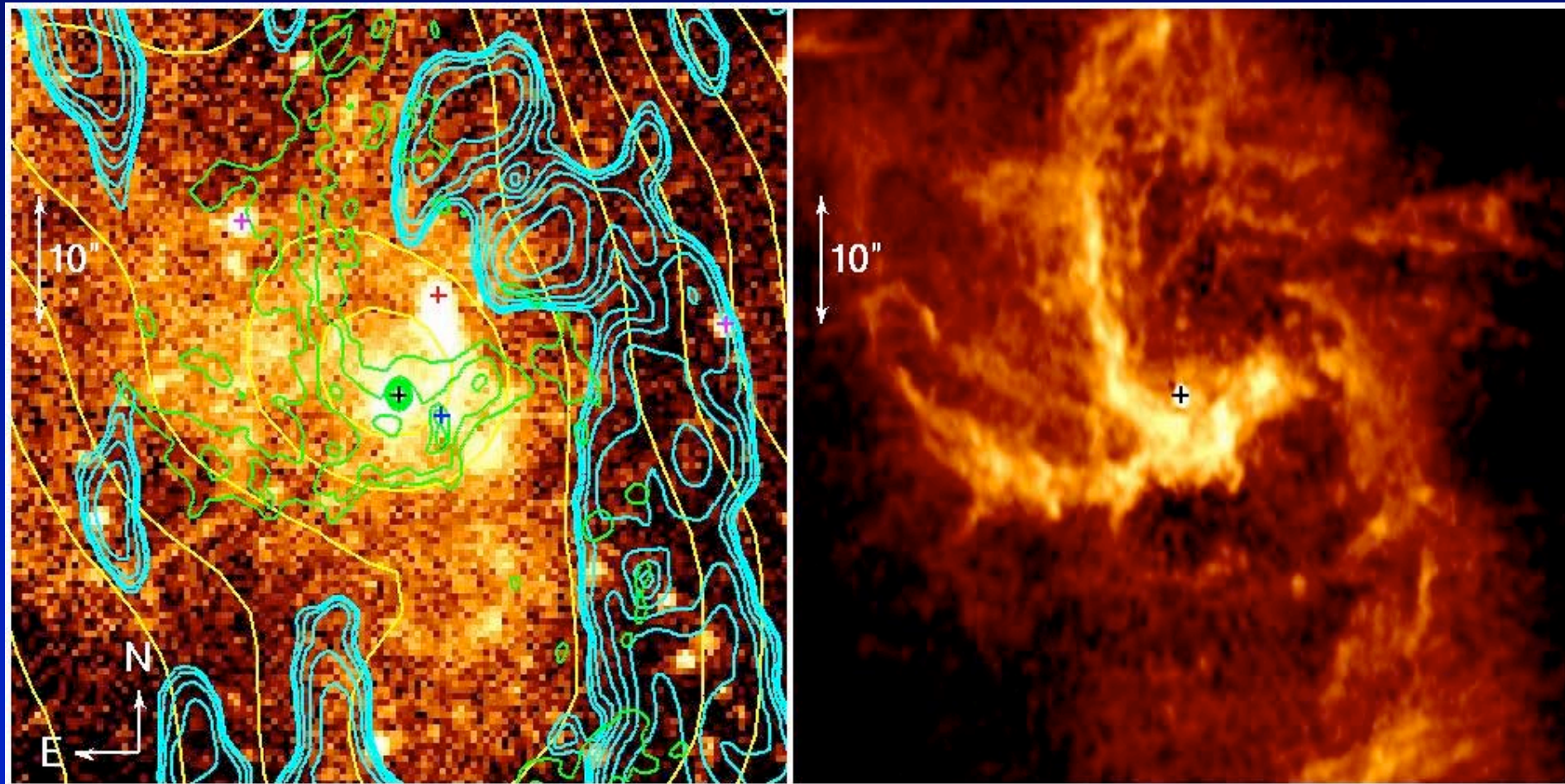


20 cm: Yusef-Zadeh & Morris

6 cm: Yusef-Zadeh & Morris



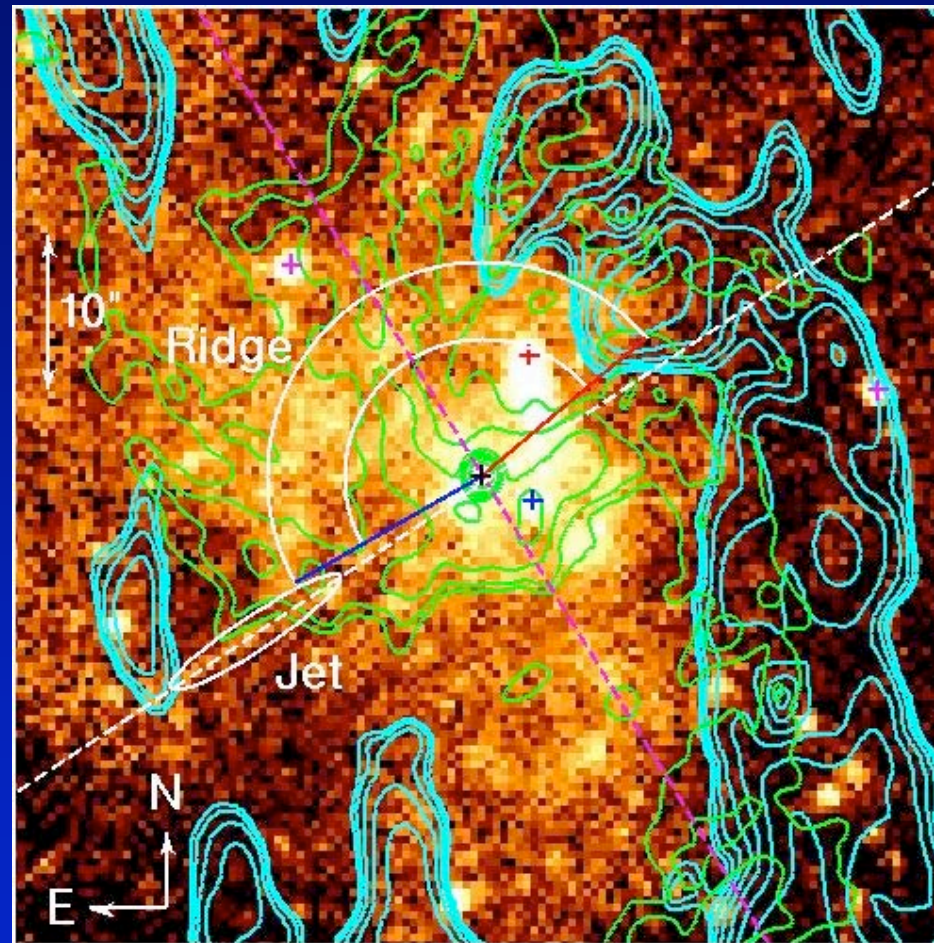
## 20 cm (yellow), HCN (blue), 6 cm (green) Contours



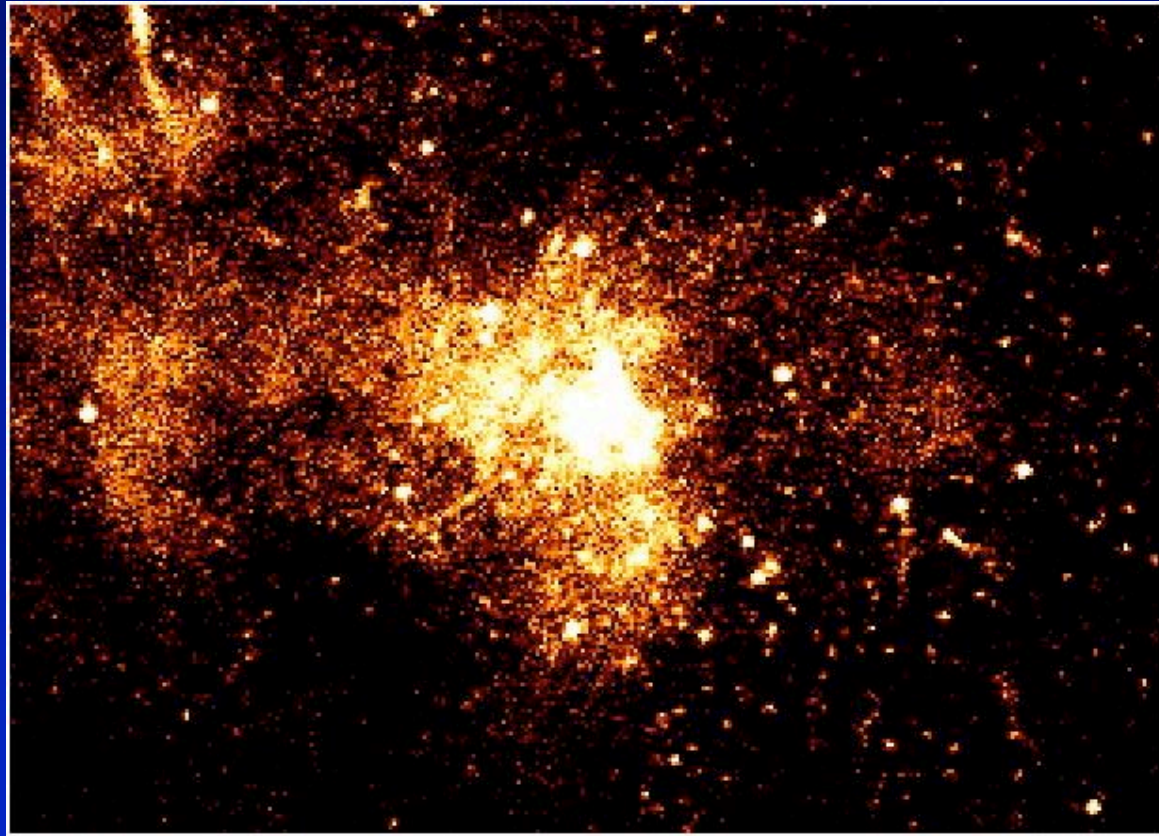
6 cm: Yusef-Zadeh & Morris



# X-ray View of the Central Parsec of the Milky Way



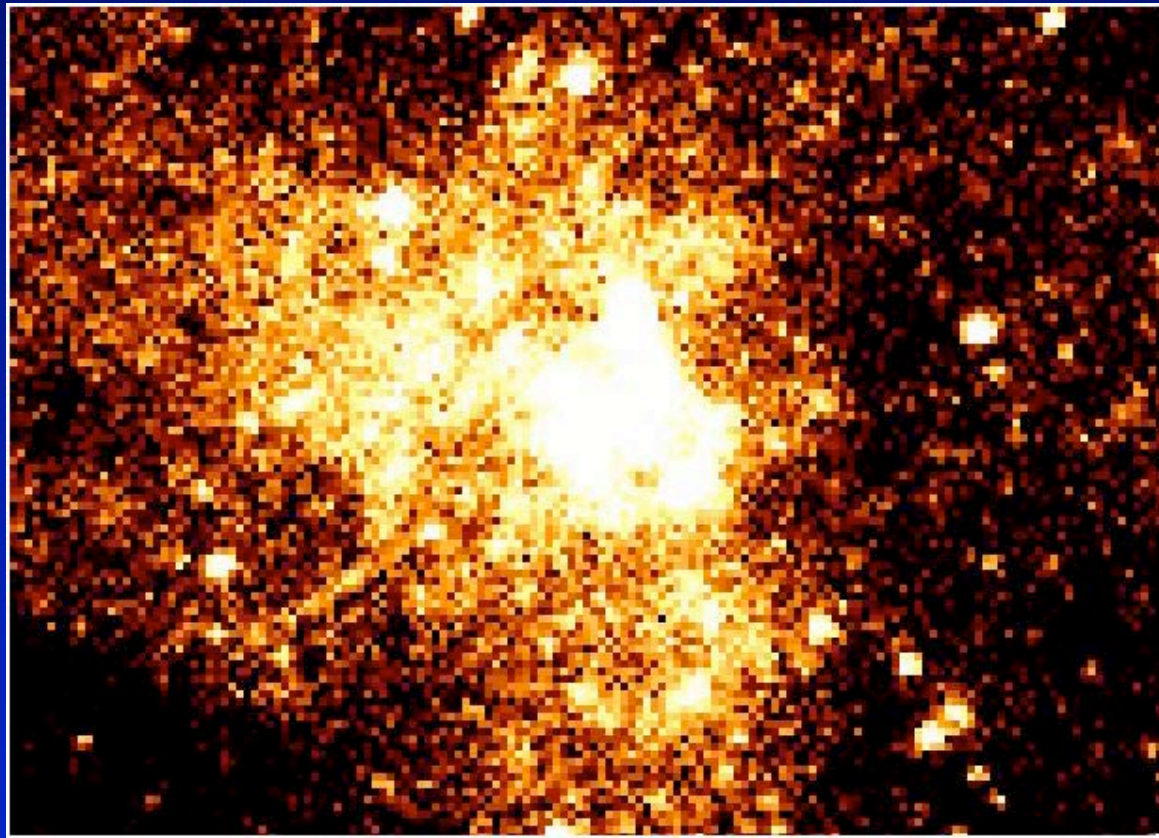
# X-ray View of the Central Few Parsecs of the Milky Way



725 ks exposure using ACIS subpixel analysis

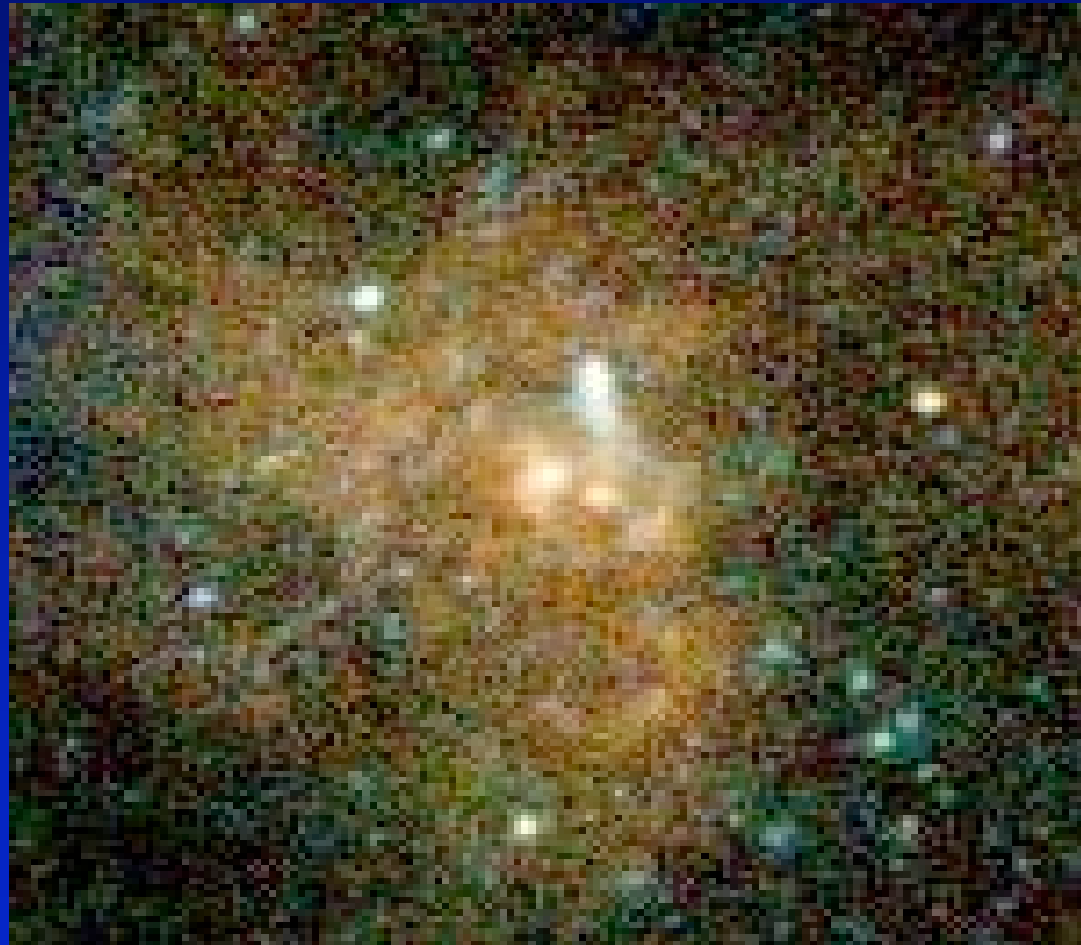


## X-ray View of the Central Parsec of the Milky Way



725 ks exposure using ACIS subpixel analysis

## Three-color X-ray View of Sgr A West and Sgr A\*



Credit: NASA/MIT/F.K. Baganoff et al.

## Stand-off Distance for Central Parsec Cluster Stellar Wind - Sgr A East Interaction

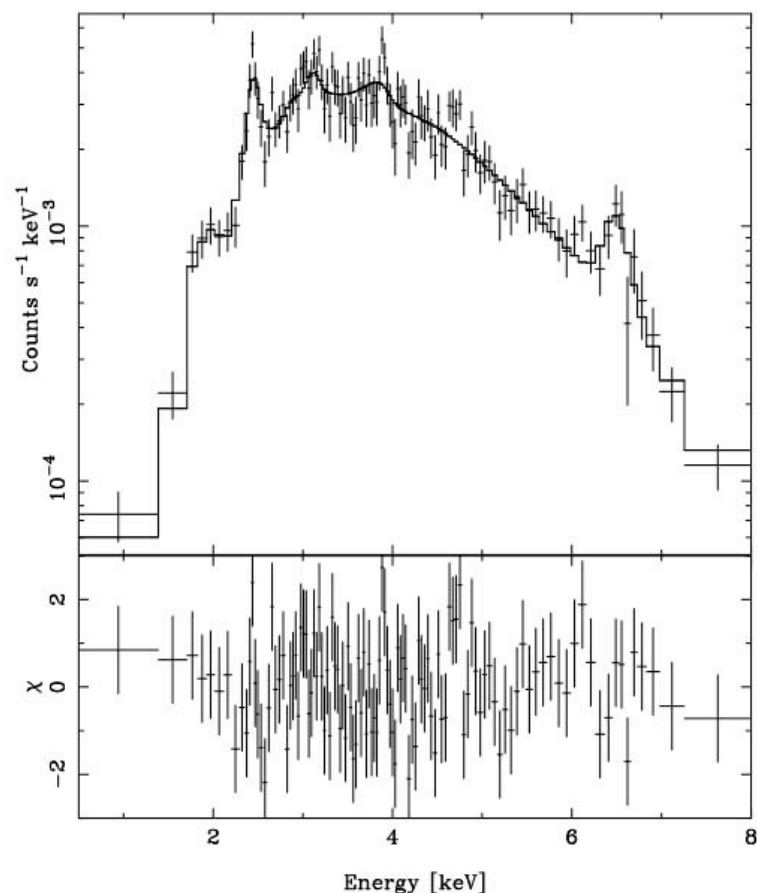
$$R \sim 45 \left( \dot{M}_{\text{sw}} / 10^{-3} \text{ Msun/yr} \right)^{1/2} \\ \times \left( N_{\text{SN}} / 10 \text{ cm}^{-3} \right)^{-1/2} \left( v_{\text{sw}} / 100 \text{ km/s} \right)^{-1/2} \\ \times (v_{\text{sw}}/c_s) \text{ arcsec} \quad (\text{or } \sim 1.8 \text{ pc})$$

Consistent with radius of X-ray ridge feature to within a factor of  $\sim 2$

⇒ Central parsec is inside the Sgr A East SNR

⇒ Role for SNR and windy stars in regulating accretion onto SMBHs in normal galaxies

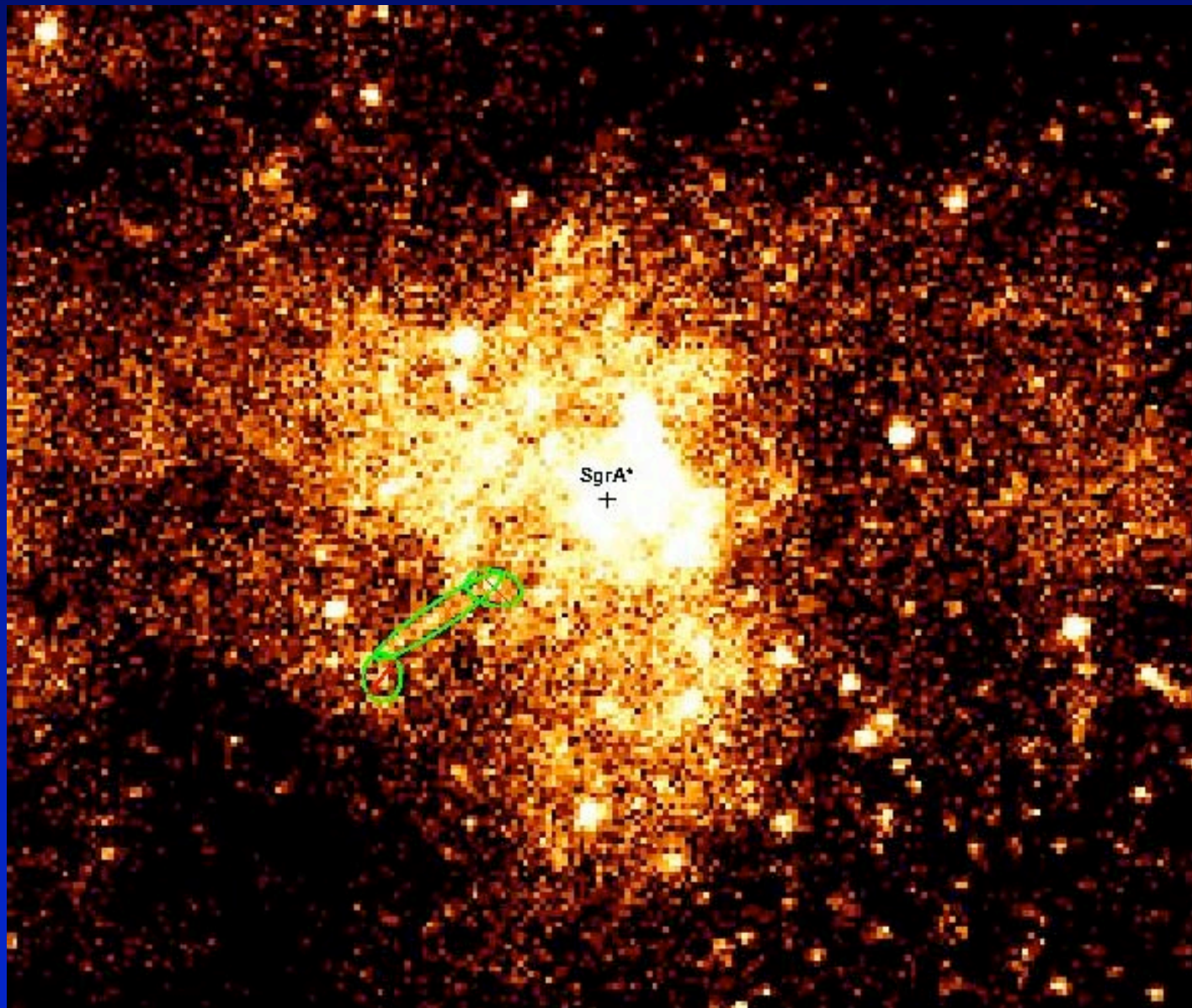
# Spectrum of Sgr A Ridge



- APEC + NEI thermal plasma
  - $kT1 = 1$  keV (to fit Si, S, Ar, Ca)
  - $kT2 = 5.6$  keV (to fit Fe)
  - Soft component is CIE
  - Hard component is NIE
- $L_x = 3.0 \times 10^{33} \text{ erg s}^{-1}$  (hard comp)
- $B_x = 1.4 \times 10^{31} \text{ erg s}^{-1} \text{ arcsec}^{-2}$

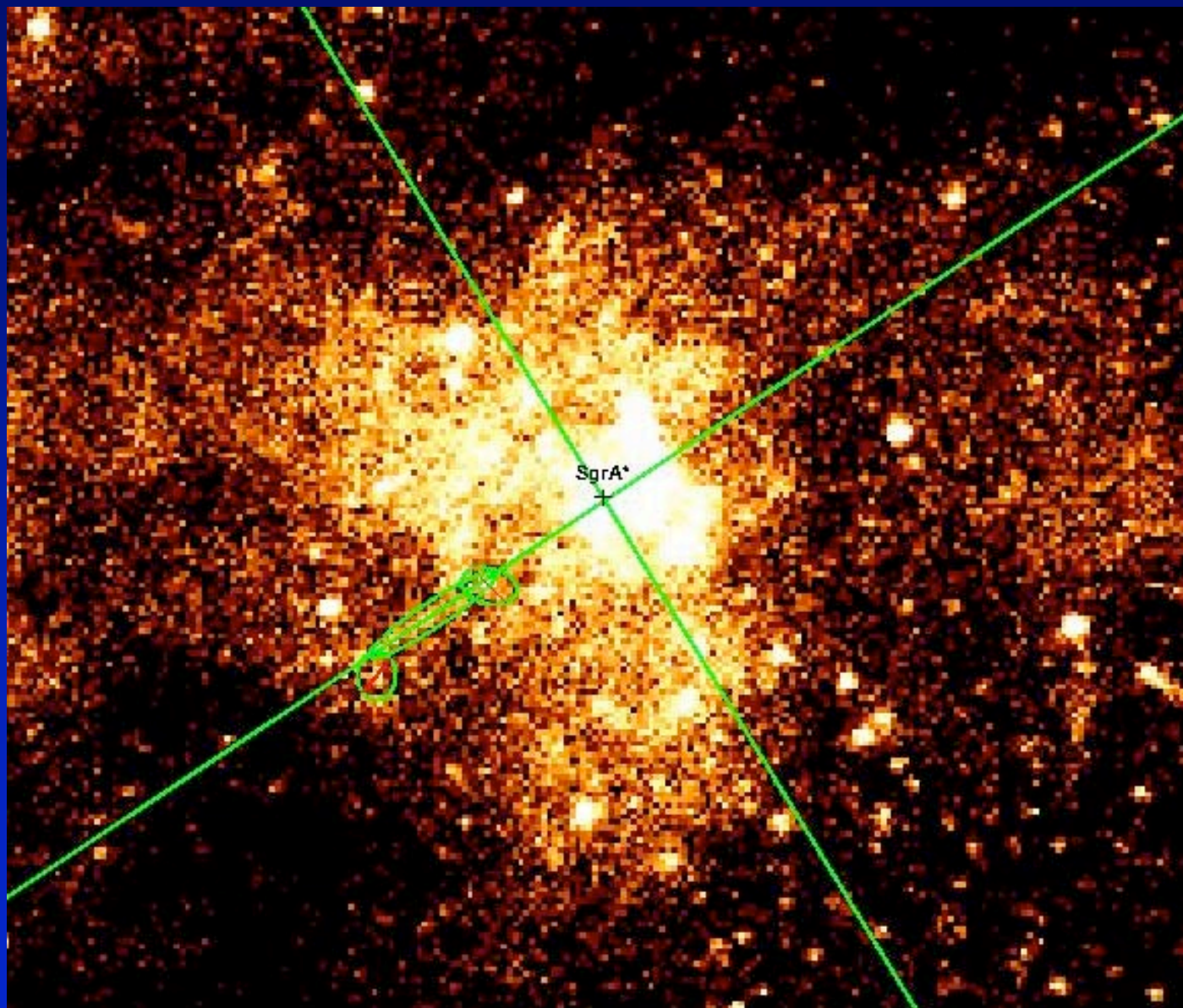


## Possible X-ray Jet from Sgr A\*

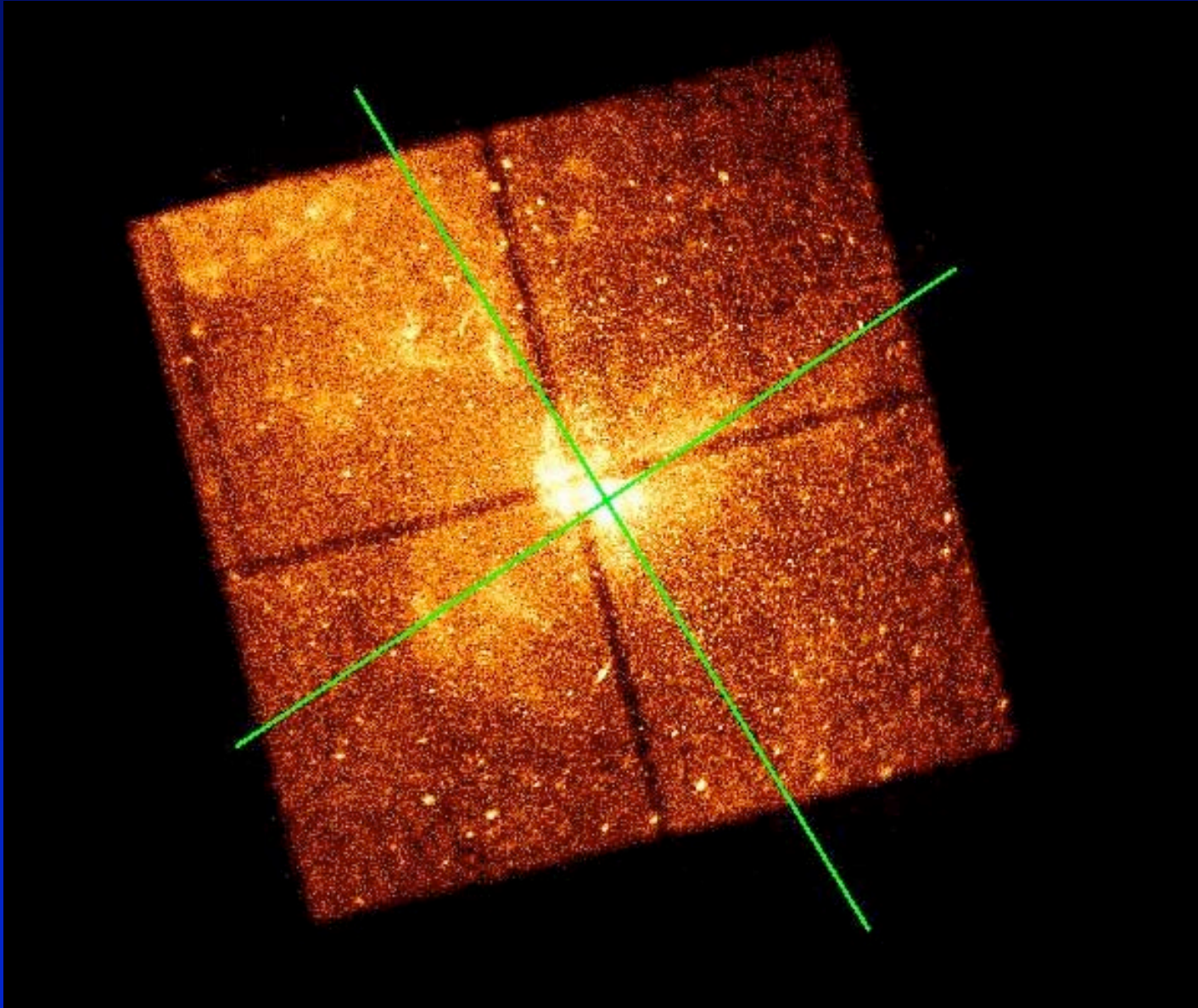




## Jet Oriented Nearly Perpendicular to Galactic Plane

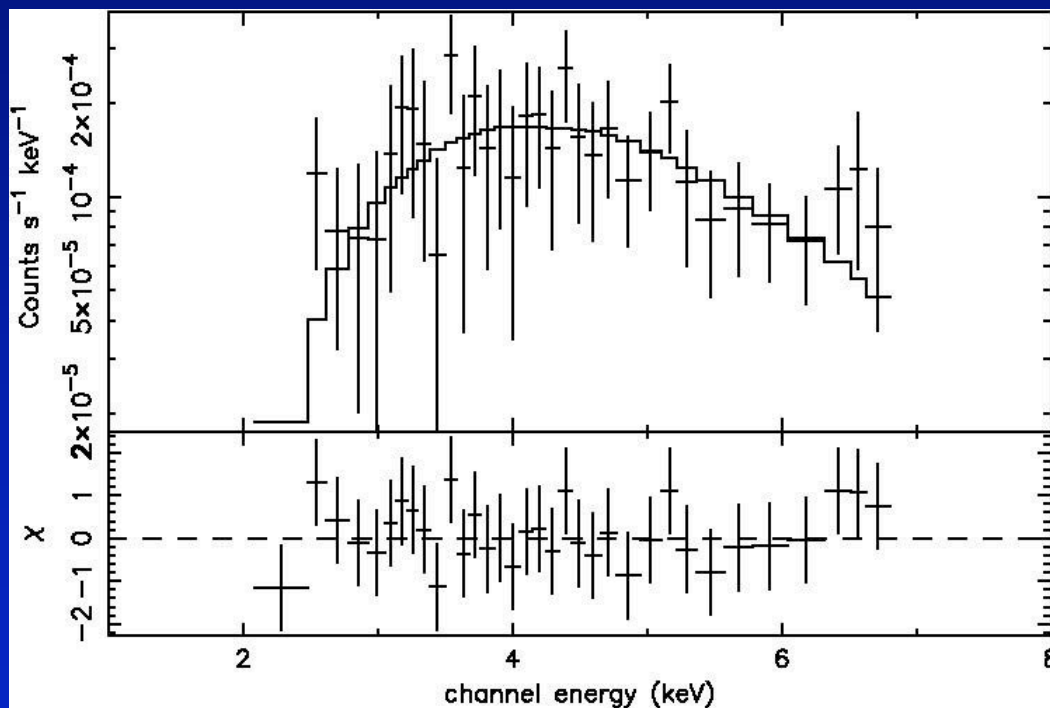


## Jet Orientation Bisects the Bipolar Lobes



# Spectrum of Possible Jet-like Feature Near Sgr A\*

## Absorbed Power-law Model – Dust Corrected



- $\Gamma = 1.8$
- $N_H = 8.0 \times 10^{22} \text{ cm}^{-2}$
- May 2002 (1st epoch)
- July 2005 (2nd epoch)
- Search for large proper motions of knots in jet

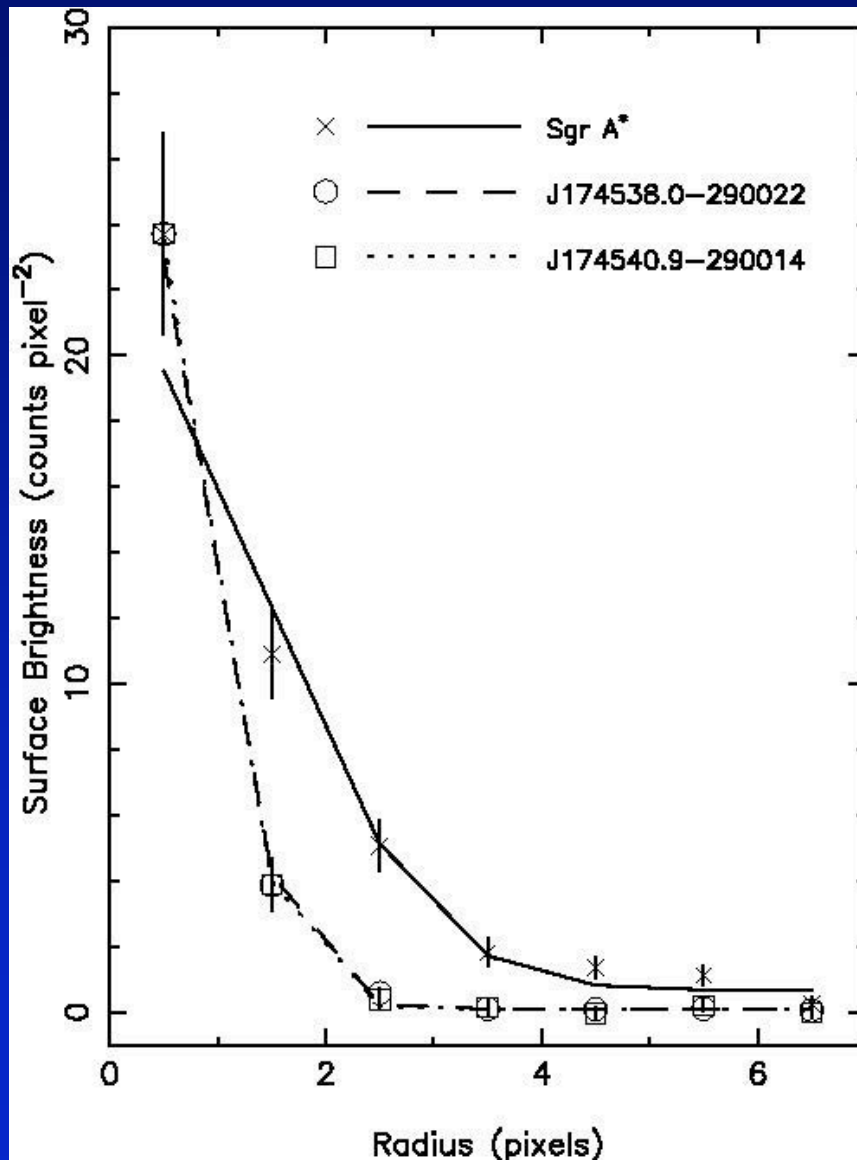


## Summary - X-ray Jet

- Discovery of an apparent X-ray jet from the Milky Way's central black hole
- Not seen in any other waveband
- Jet is 1 light-year long and located 1.5 light-years from the black hole
- Jet aligned with large-scale bipolar X-ray lobes
- Lobes may be due to past ejections or outflows from the supermassive black hole
- Strongly suggests we are seeing "fingerprints" of activity over the past few thousand years
- X-ray flares tell us about the current activity

# X-ray Emission at Sgr A\* is Extended

Baganoff et al. 2003, ApJ, 591, 901

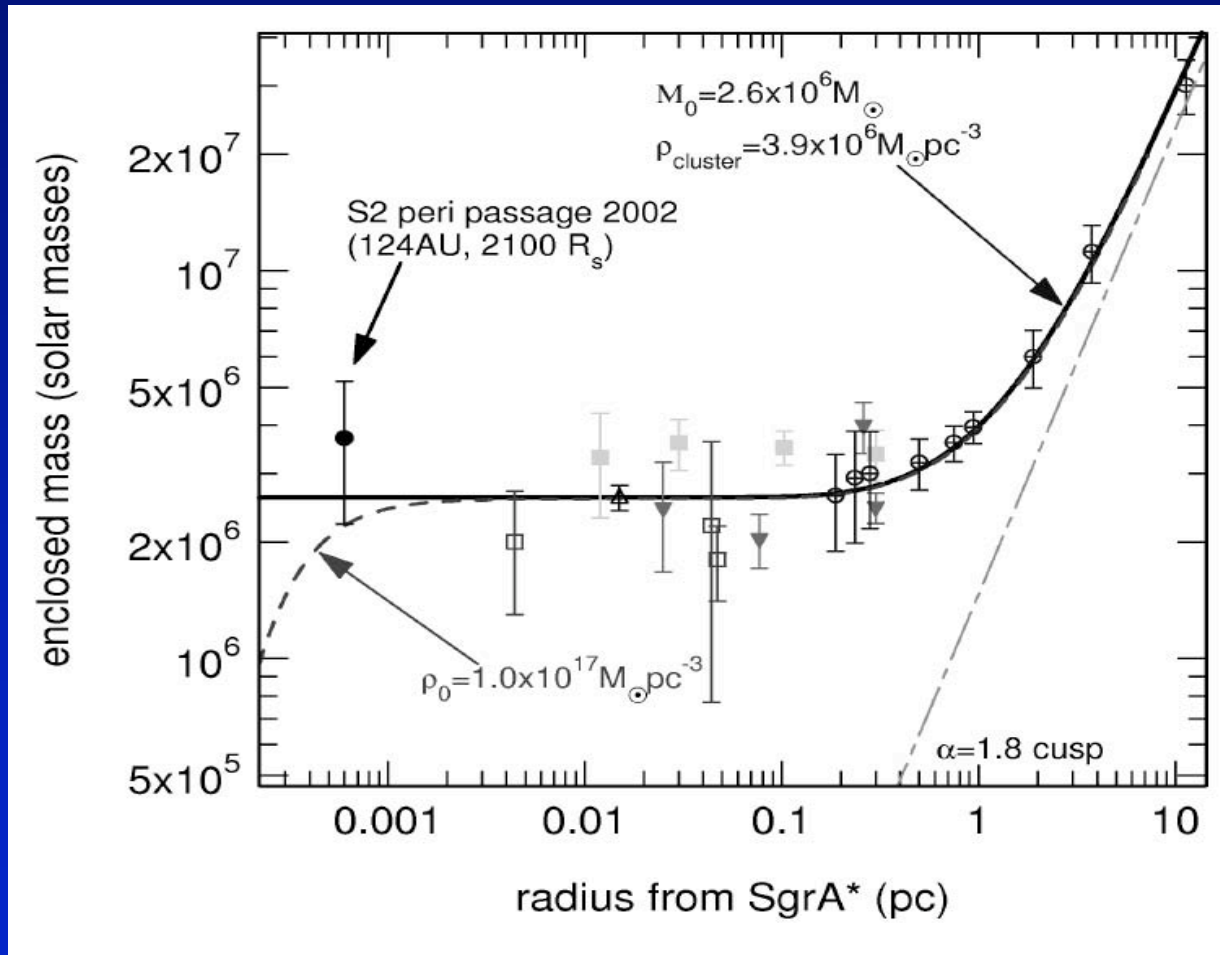


- Intrinsic size of emission at Sgr A\* is about 1.4 arcsec (FWHM)
- Consistent with Bondi accretion radius for a  $3 \times 10^6$  solar-mass black hole



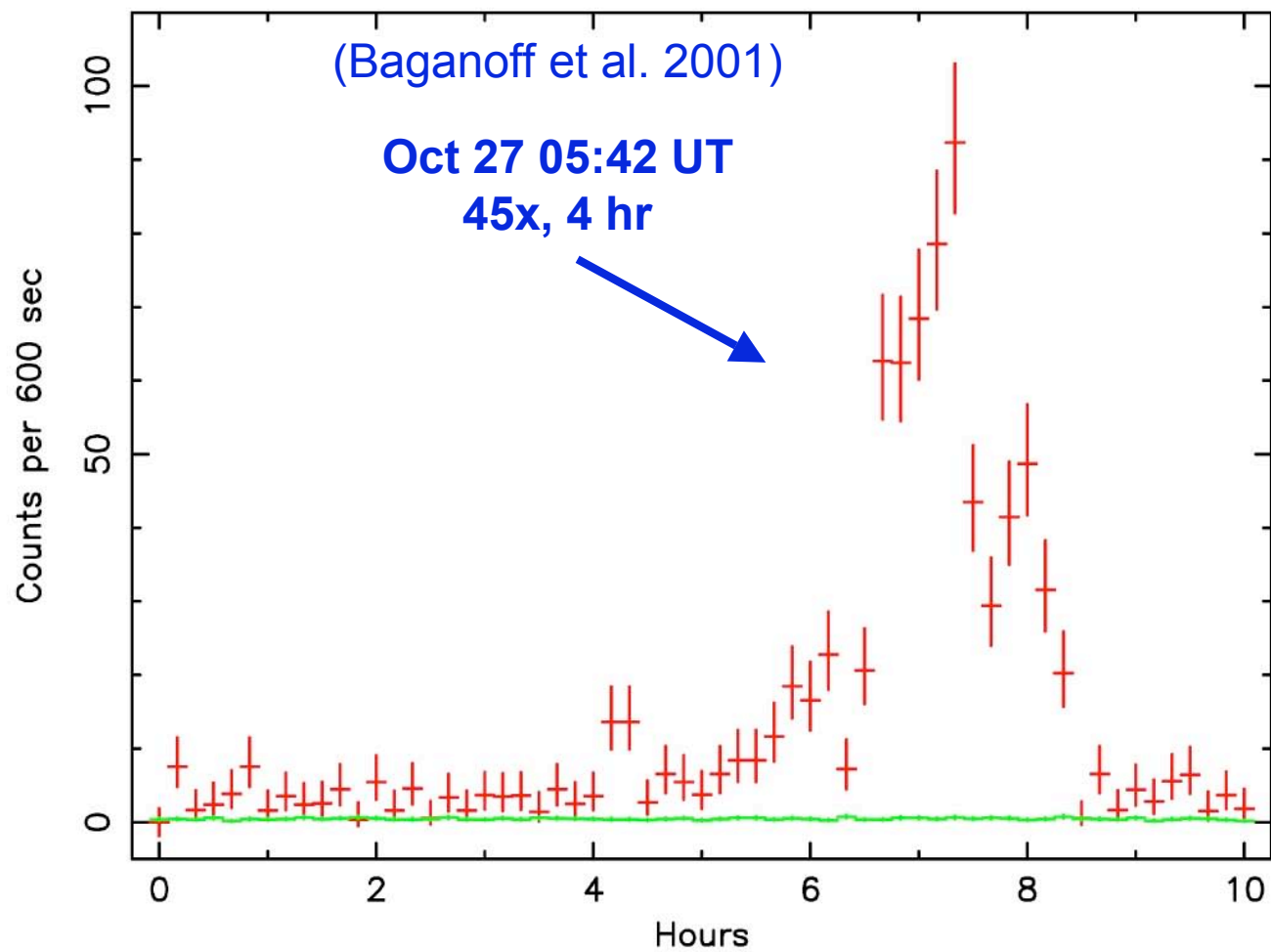
# Enclosed Mass vs. Radius Around Sgr A\*

Schoedel et al. 2002, Nature, 419, 694



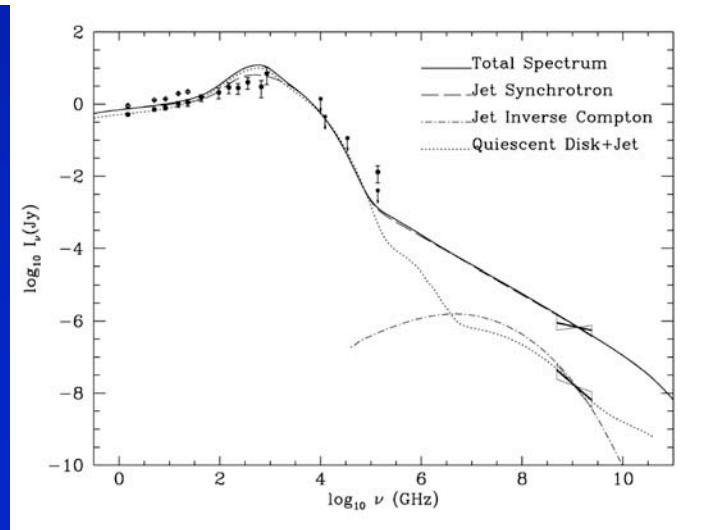
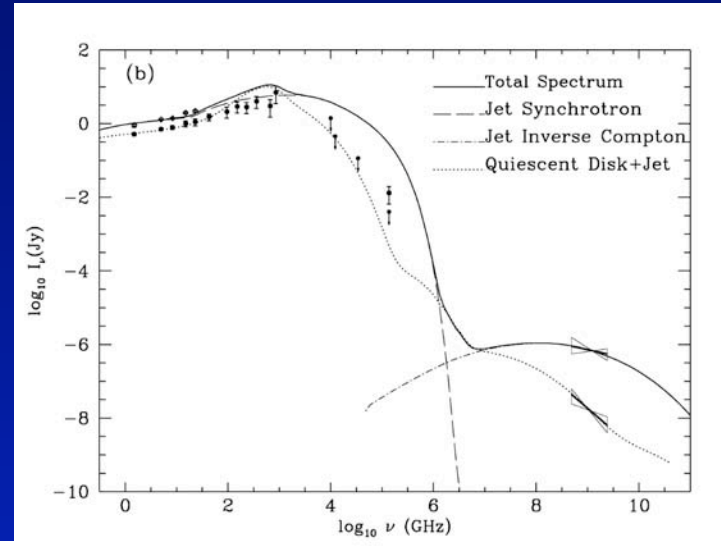
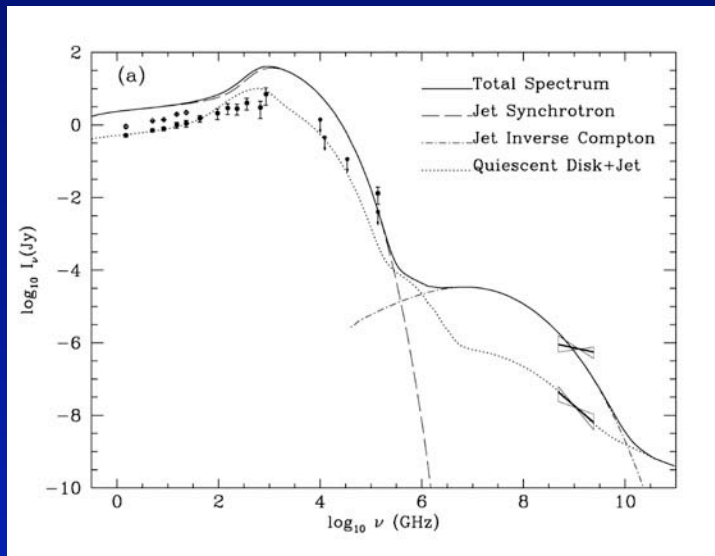
# 2000 October 26-27

OBSID 1561 – 2000:10:26:22:23:32.8 (UT)



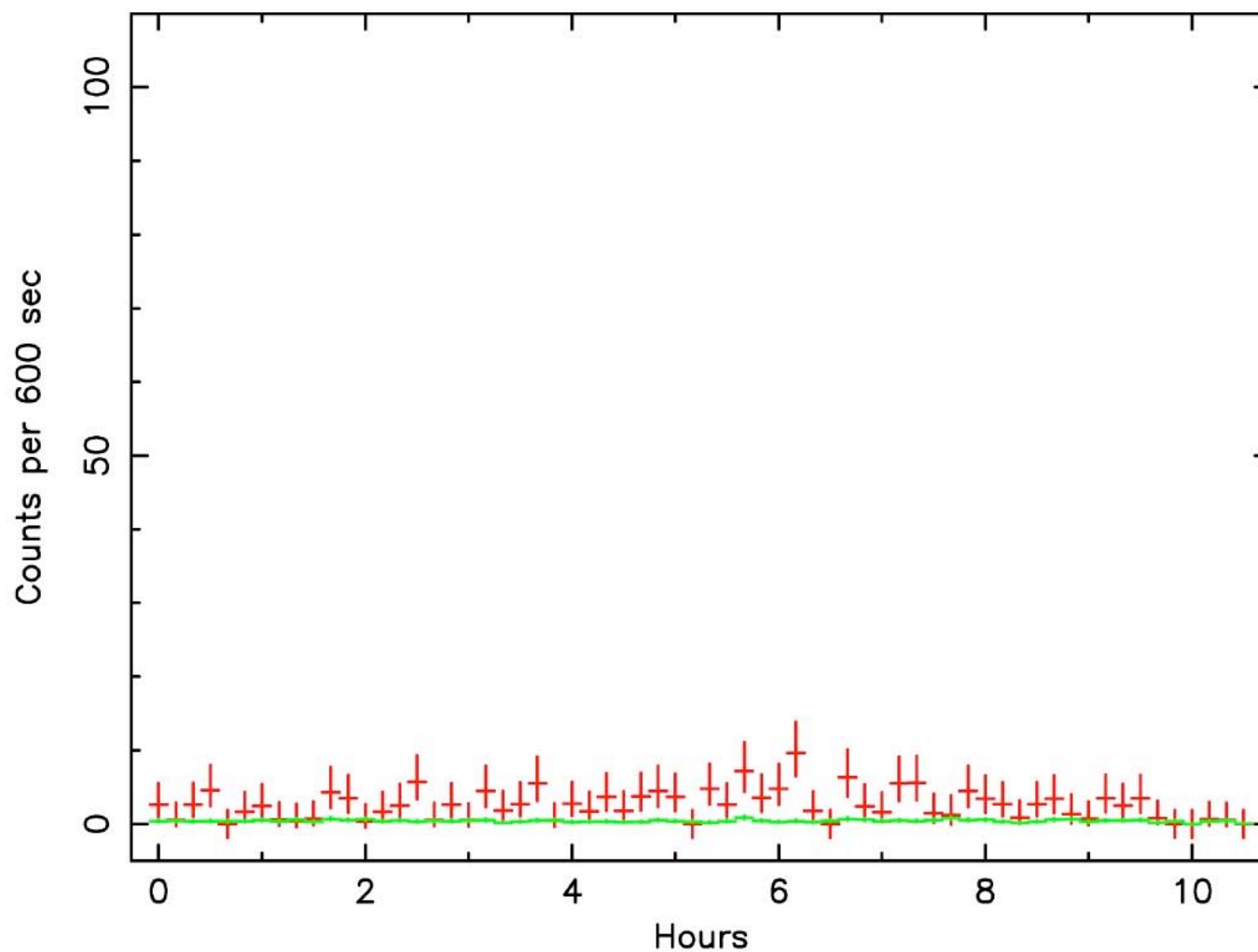
# Jet Models

Markoff et al. 2001, A&A, 379, L13



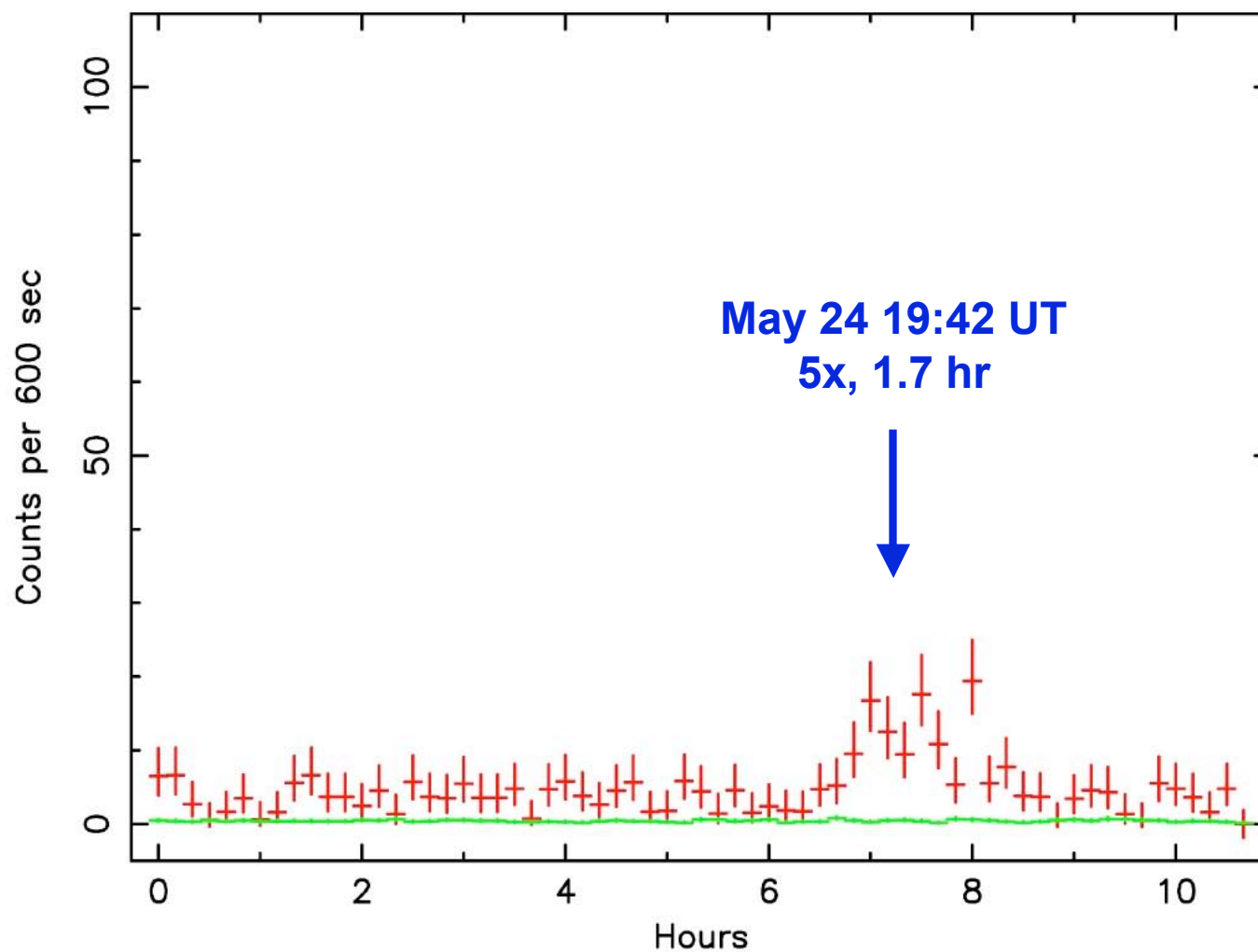
# 2002 May 22-23 – Orbit 1, Part 1

OBSID 2943 – 2002:05:22:23:27:02.7 (UT)



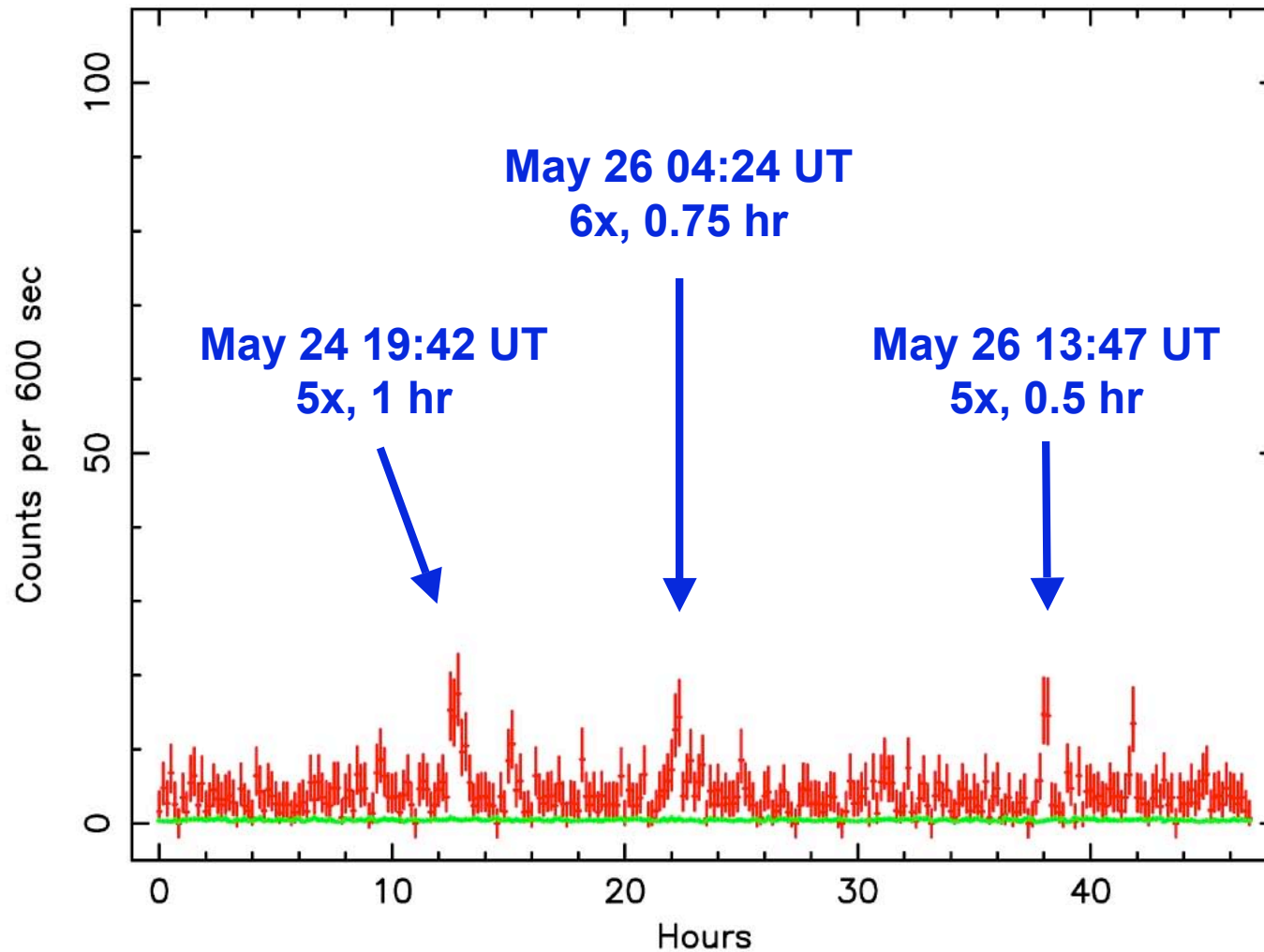
## 2002 May 24 – Orbit 1, Part 2

OBSID 3663 – 2002:05:24:12:17:02.9 (UT)



## 2002 May 25-27 – Orbit 2

OBSID 3392 – 2002:05:25:15:39:28.3 (UT)





## 2002 May 28-30 – Orbit 3

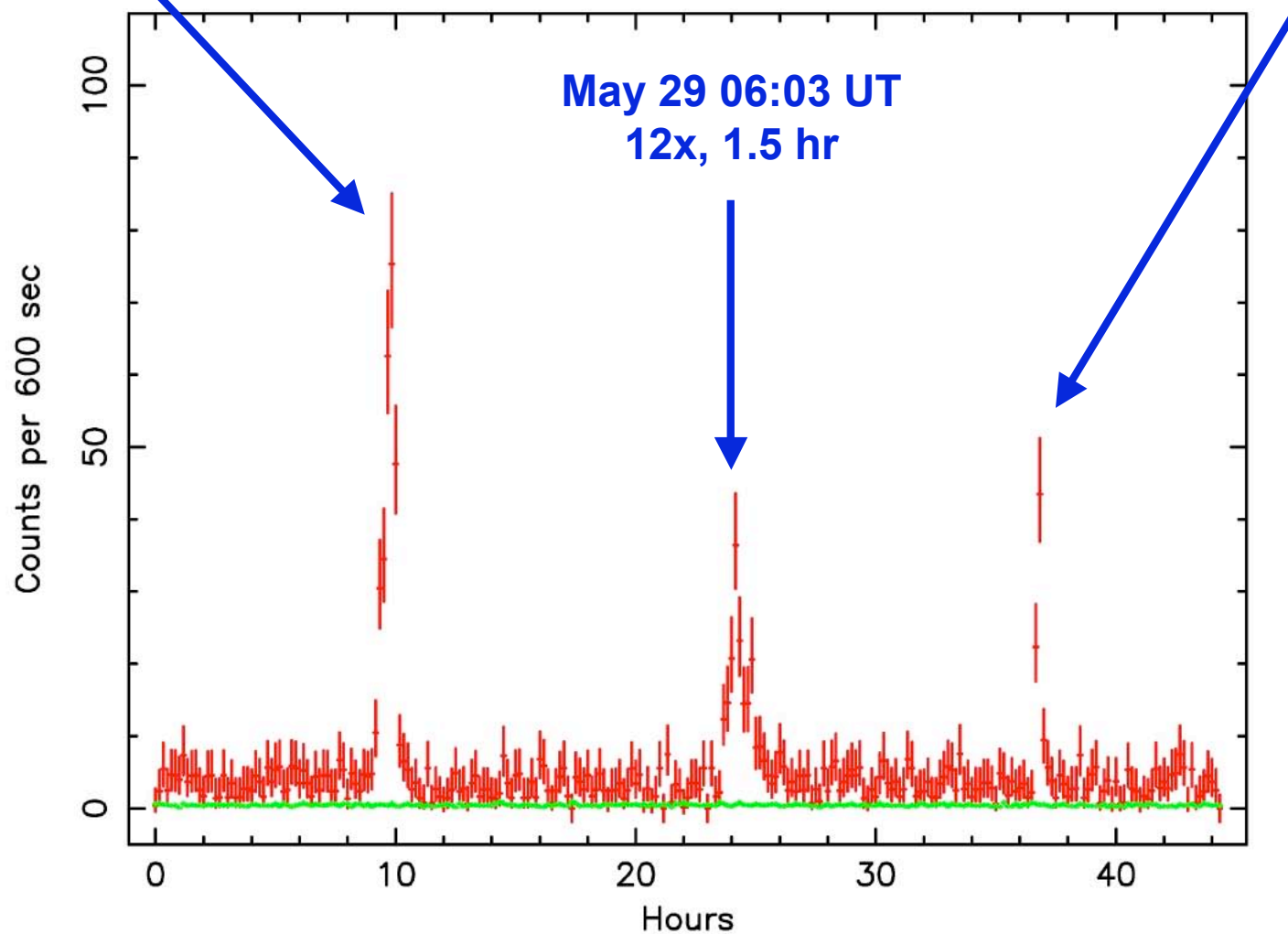
May 28 15:36 UT

25x, 1 hr

OBSID 3393 – 2002:05:28:05:58:08.2 (UT)

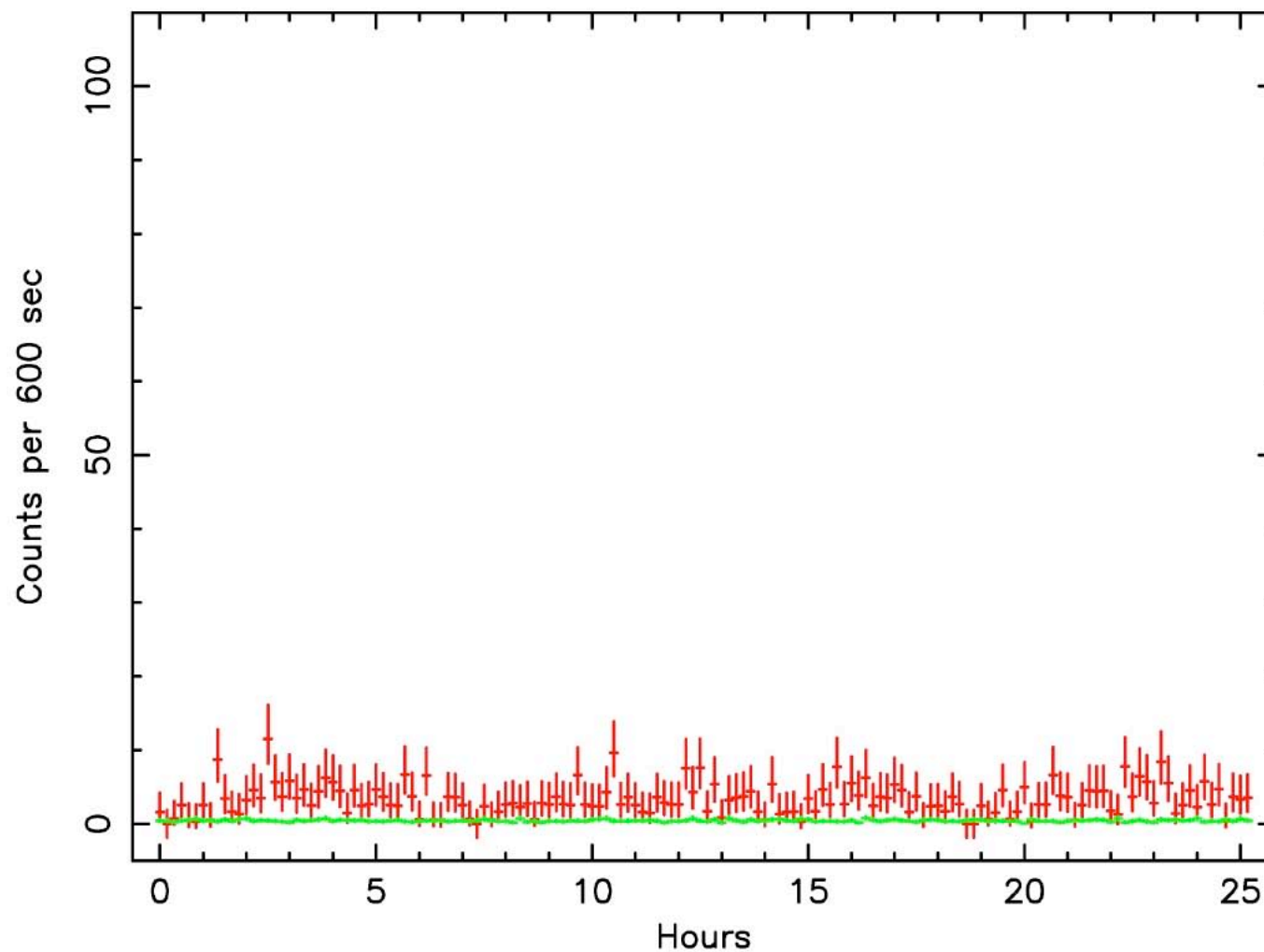
May 29 18:33 UT

13x, 0.5 hr

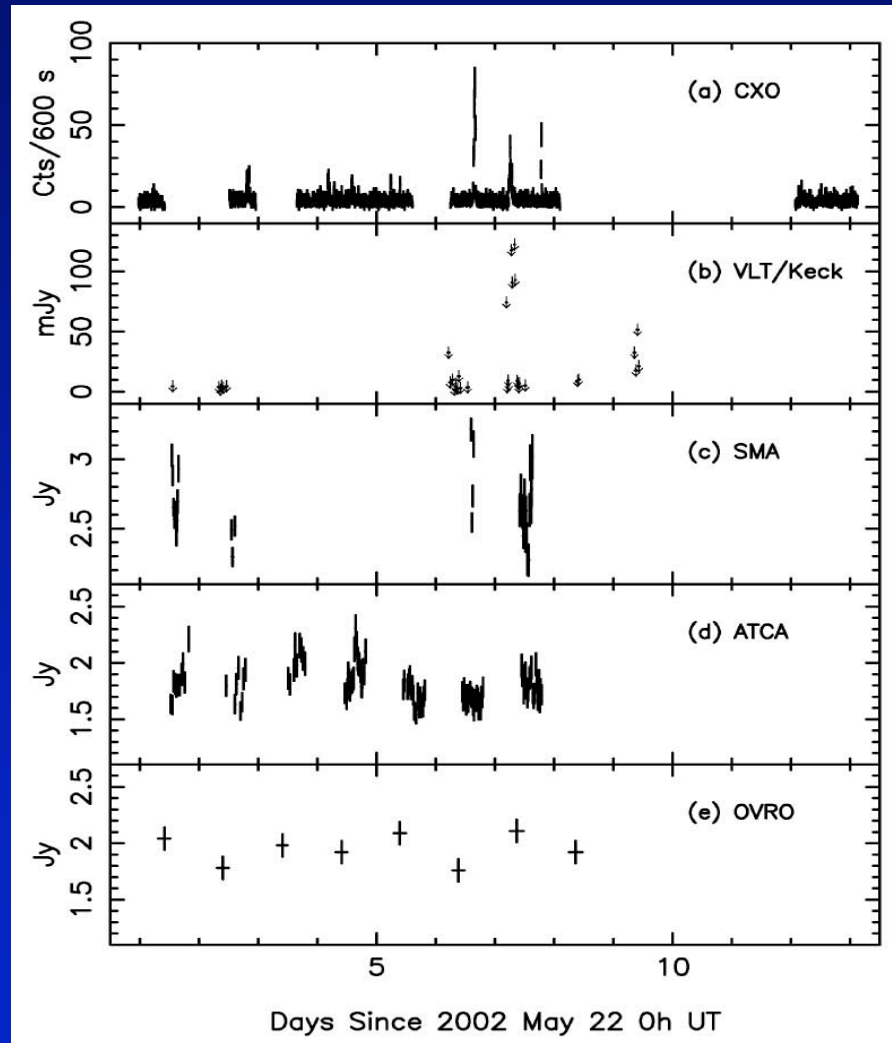


## 2002 June 3-4 – Orbit 5

OBSID 3665 – 2002:06:03:01:46:30.4 (UT)

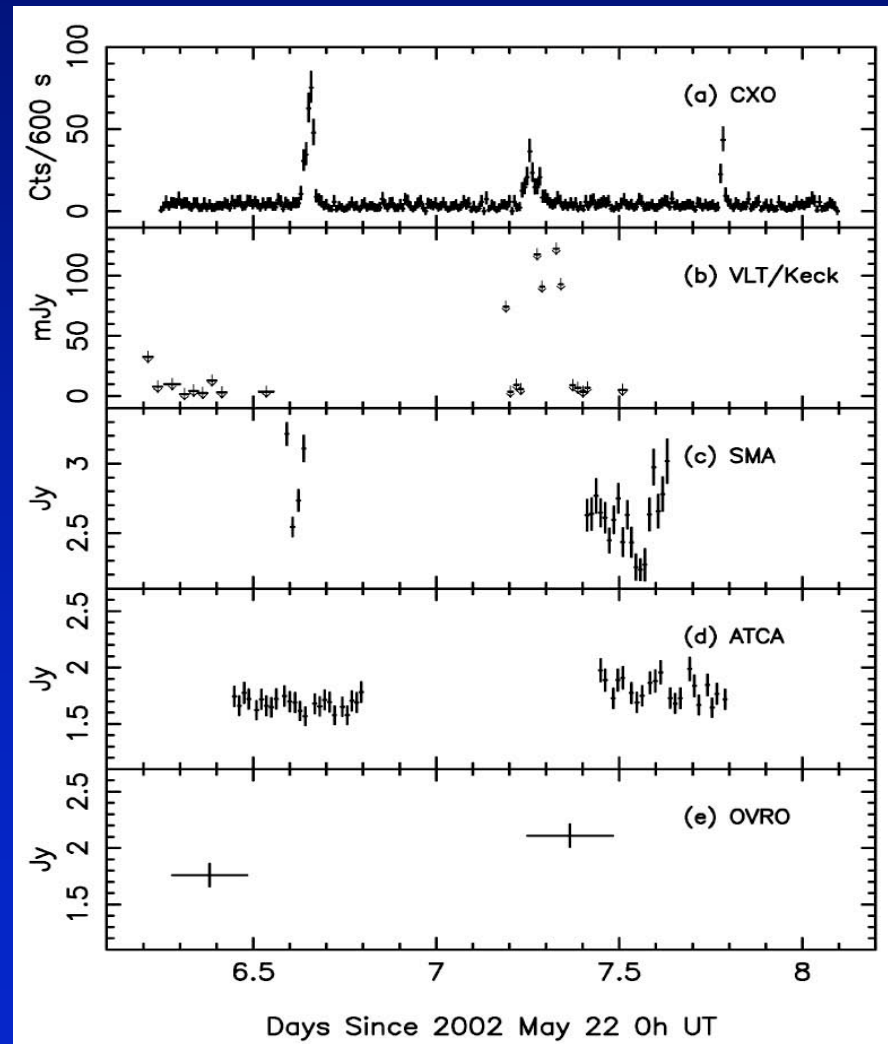


# Sgr A\* Multiwavelength Monitoring Campaign

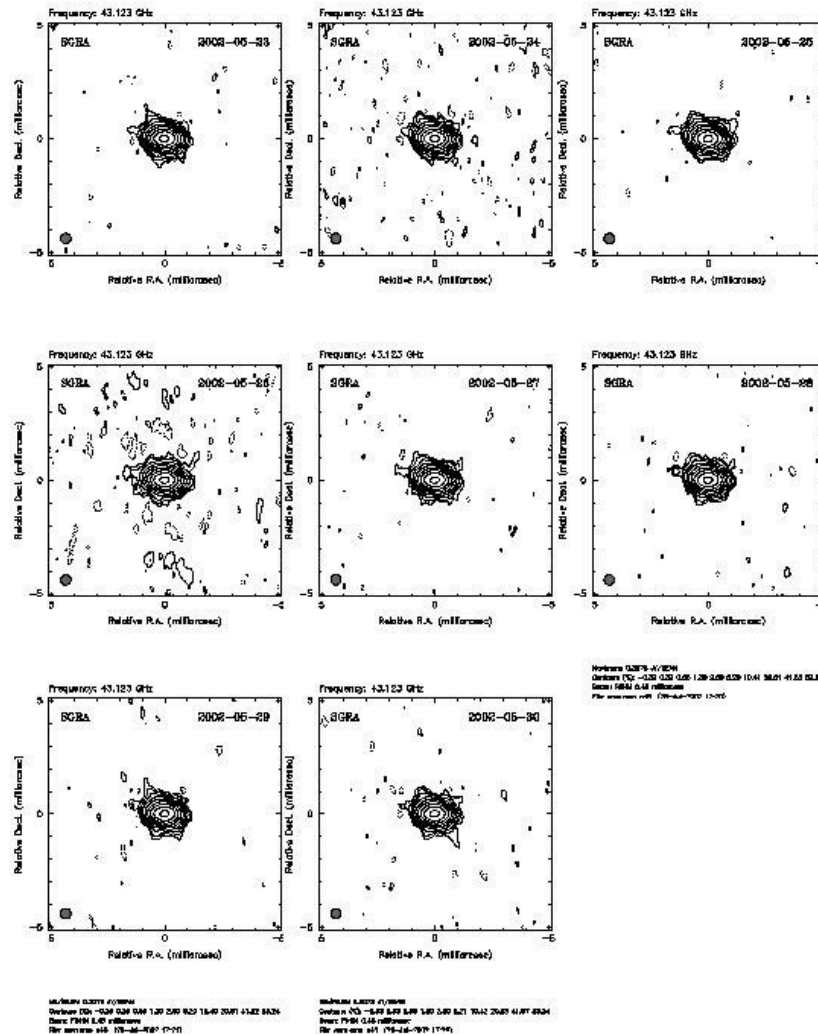




## Sgr A\* Millimeter Emission Steady During Large X-ray Flares



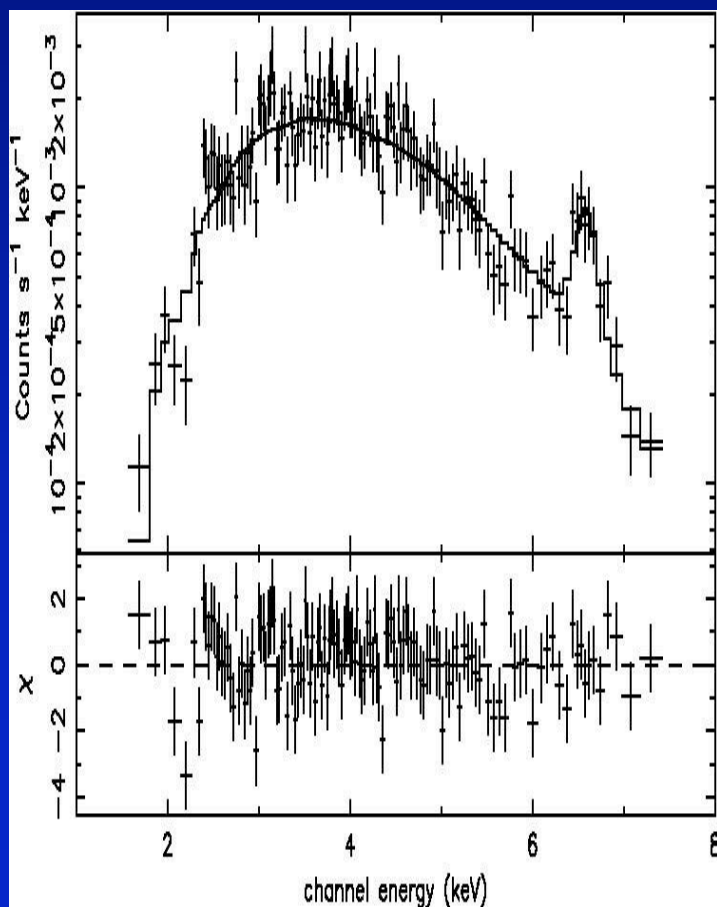
# Very Long Baseline Array – 7 mm



- No significant flux variability detected
- Upper limit about 30%
- No extended structure appeared
- Upper limit about 10 mJy

# Integrated X-ray Spectrum of Sgr A\* in Quiescence

**Model: Absorbed, Dust-Scattered, Power Law Plus Line**



$$N_H = 5.9 \times 10^{22} \text{ cm}^{-2}$$
$$\Gamma = 2.4 (2.3-2.6)$$

$$E_{\text{Fe}} = 6.59 (6.54-6.64) \text{ keV}$$

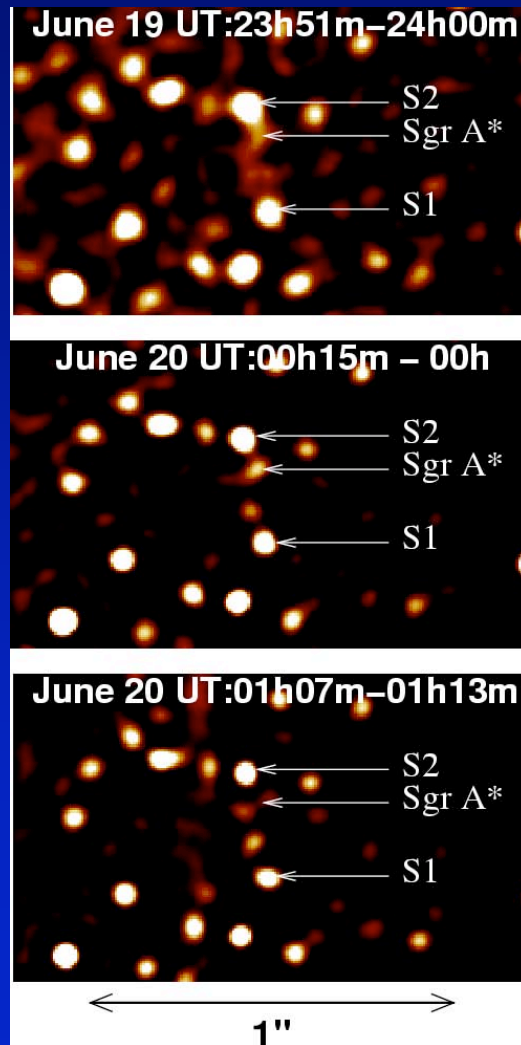
Line is narrow and NIE

$$F_X = 1.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$$
$$L_X = 1.4 \times 10^{33} \text{ erg s}^{-1}$$
$$D = 8 \text{ kpc}$$

$$\langle L_F \rangle / \langle L_Q \rangle = 14.0$$

# Sgr A\* Flare 19-20 June 2003 - VLT/AO K-band

Eckart et al. (2004)



## VLT Collaborators

A. Eckart, R. Schoedel,  
R. Genzel, T. Ott,  
C. Straubmeier, T. Viehmann

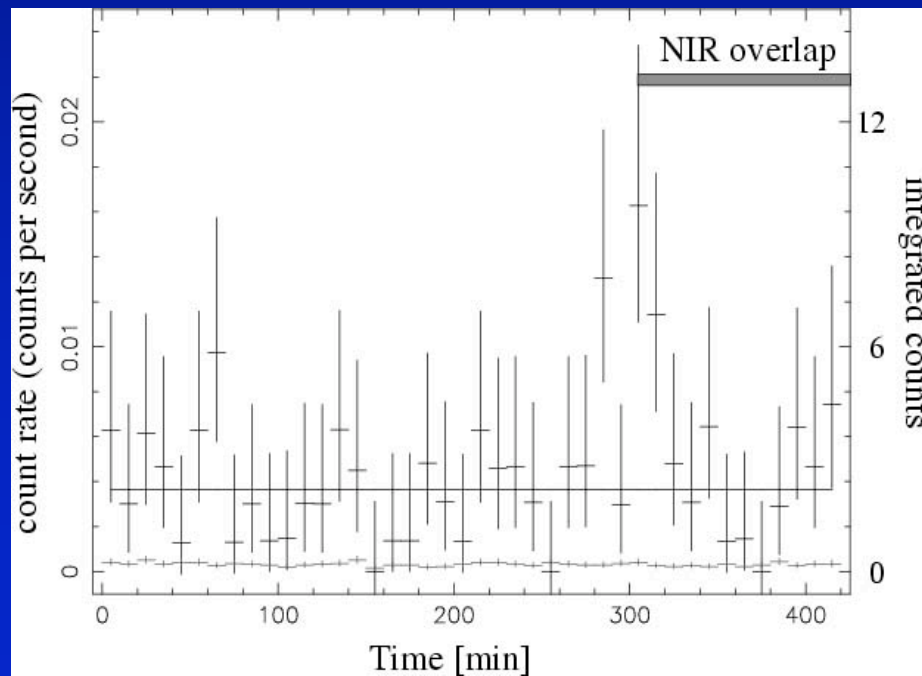


# Sgr A\* Flare 19-20 June 2003 - Chandra 2-8 keV

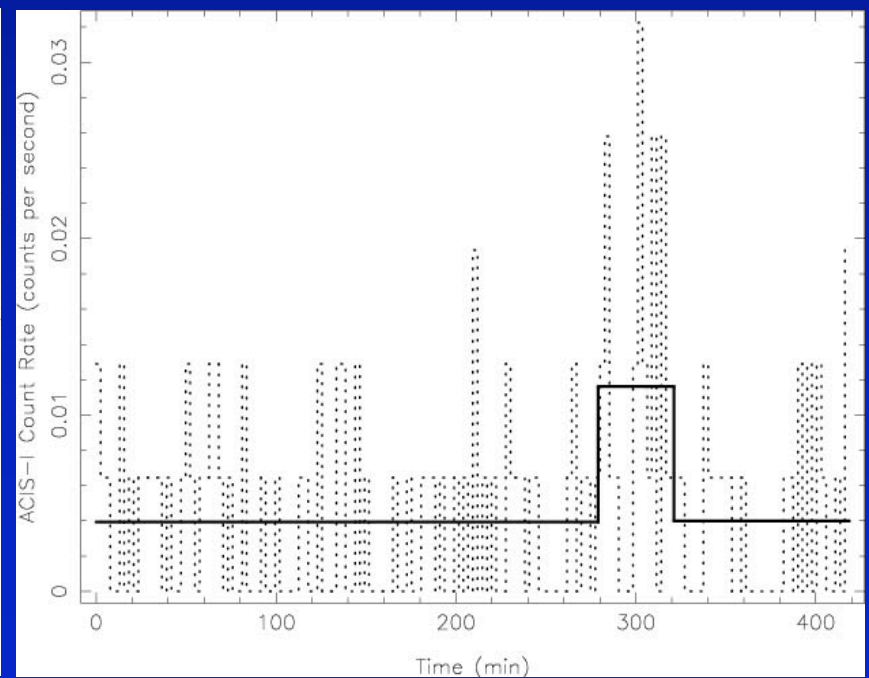
Eckart et al. (2004)

- Excess amplitude factor of  $\sim 2x$
- Duration  $\sim 40$ -60 min
- 99.92% confidence using Bayesian blocks algorithm (Scargle 1998)

Raw X-ray Light Curve

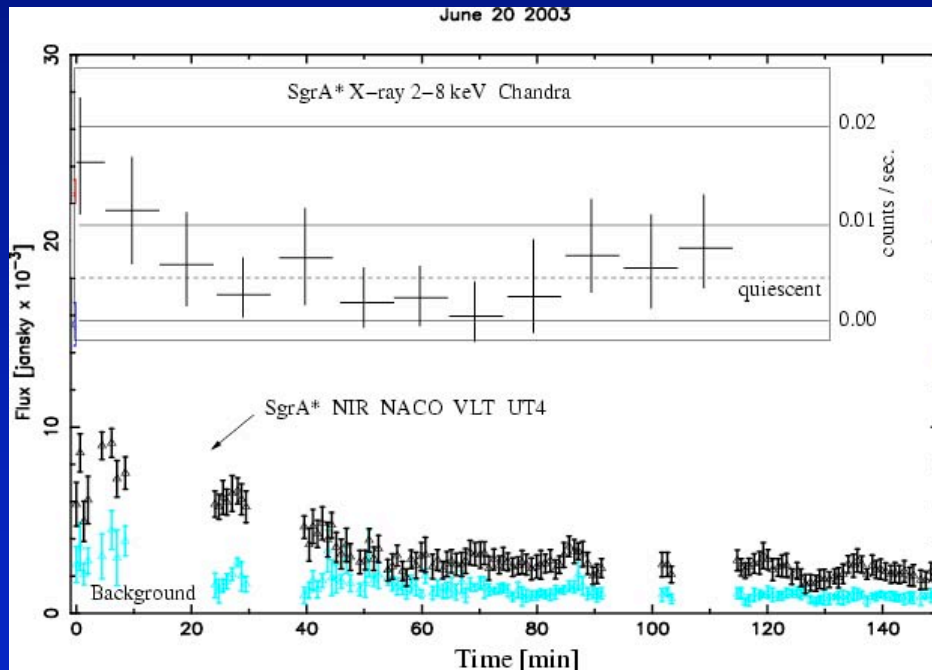


Bayesian Blocks Representation



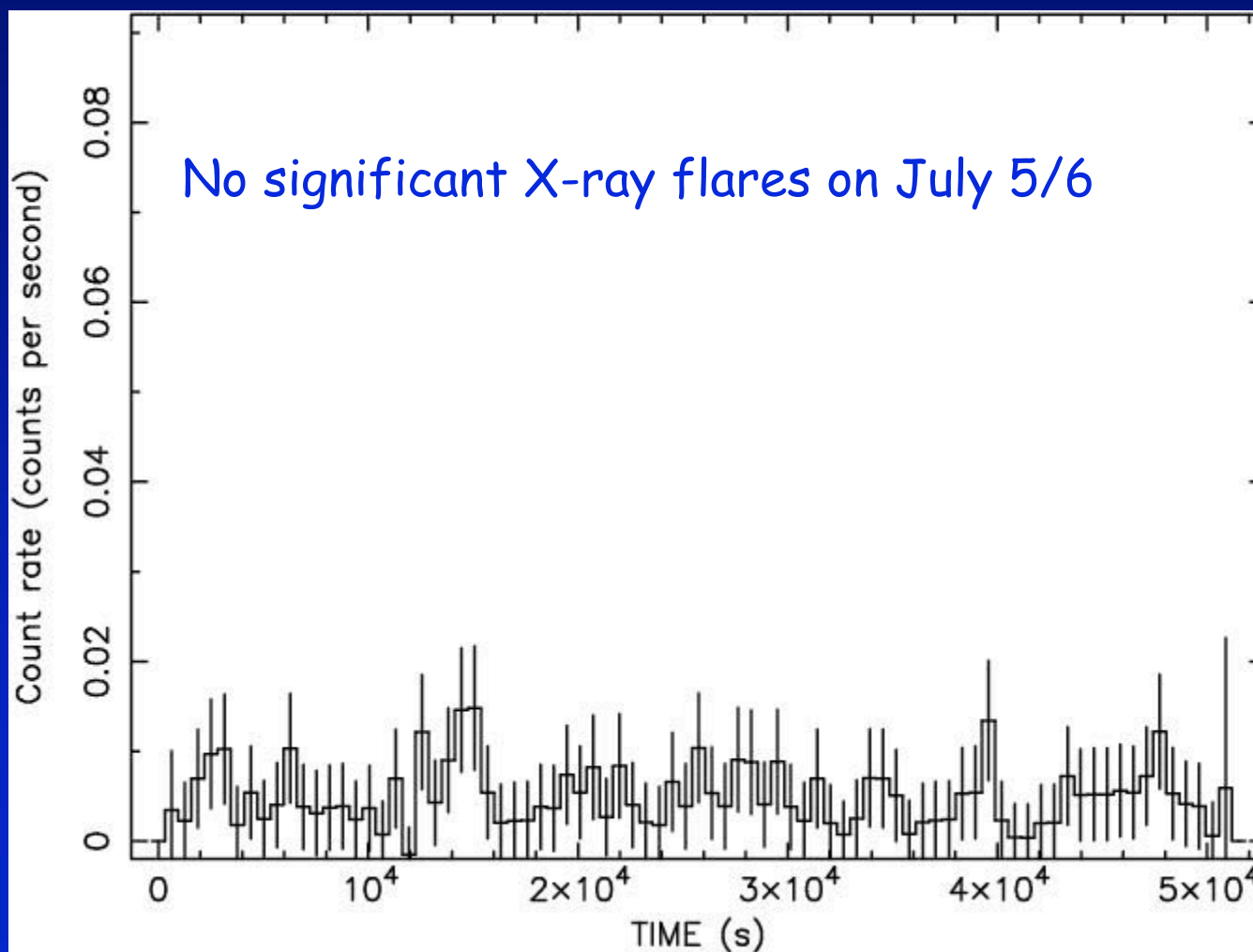
# Sgr A\* 19-20 June 2003 - NIR/X-ray Flare

Eckart et al. (2004)

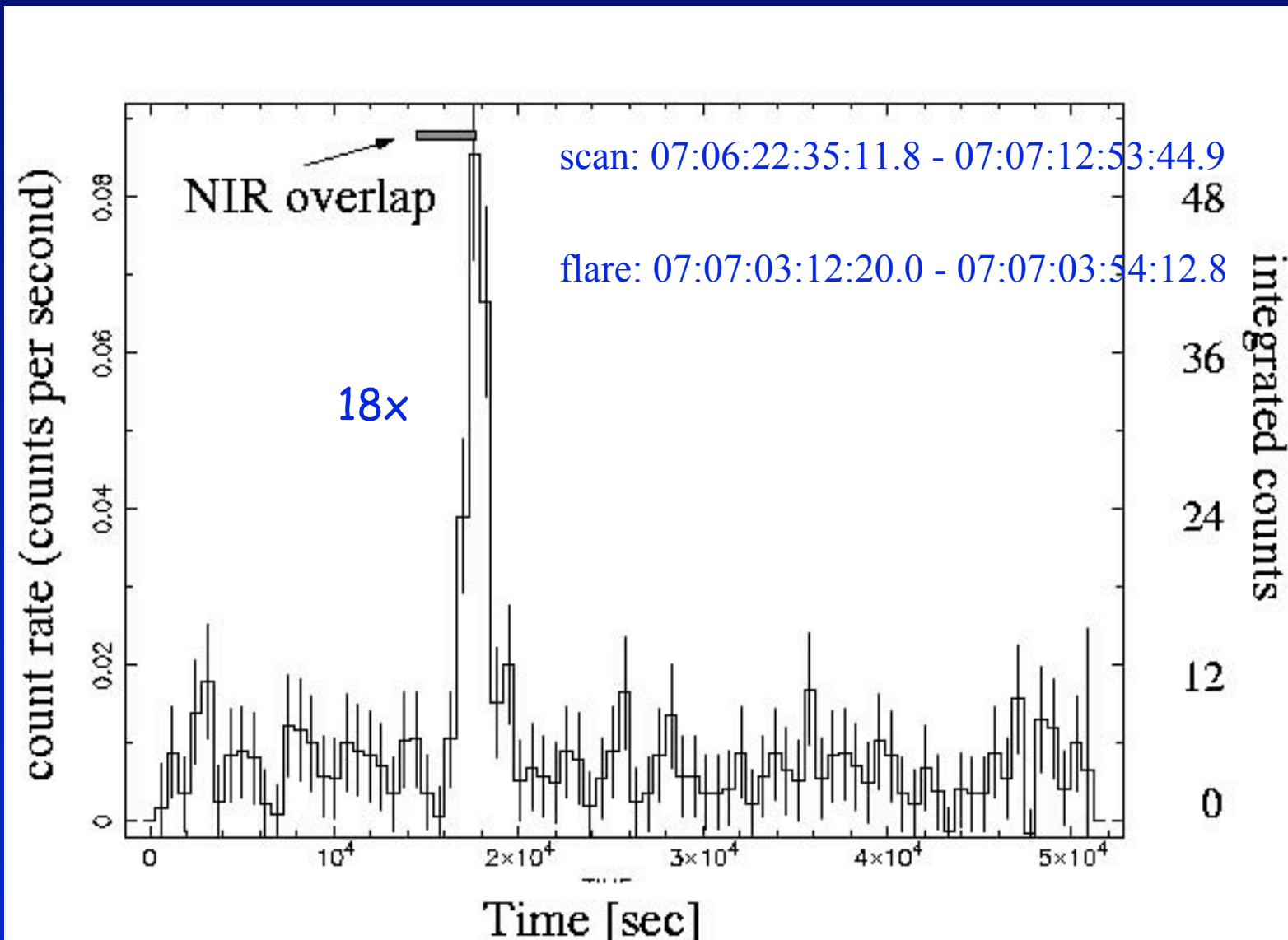


- First detection of *simultaneous* X-ray and NIR flaring
- In this case at least, X-ray and NIR photons appear to come from *same* electron population
- $L_x \sim 6 \times 10^{33} \text{ erg s}^{-1}$
- $L_{\text{nir}} \sim 5 \times 10^{34} \text{ erg s}^{-1}$
- Spectral index  $\sim 1.3$
- X-rays coincident within 180 mas
- NIR coincident within 14 mas
- X-ray flares *are* from Sgr A\*!

## 2004 July Sgr A\* Campaign

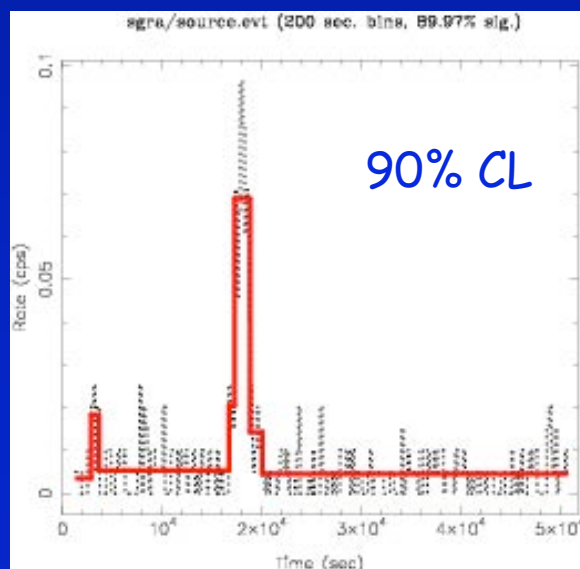
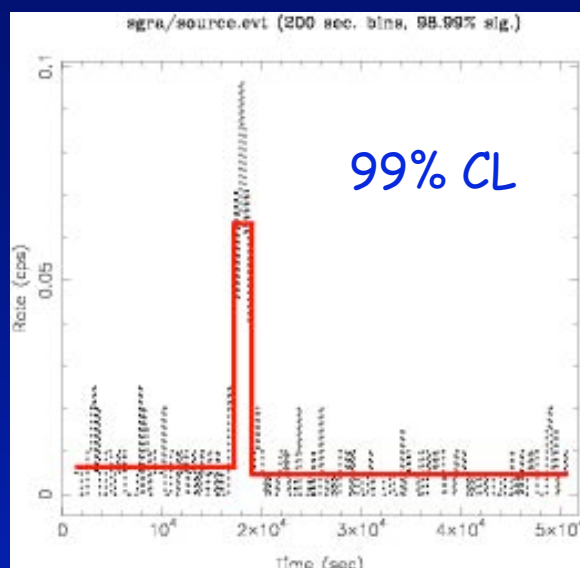


## July 2004: Detection of a Strong X-ray flare



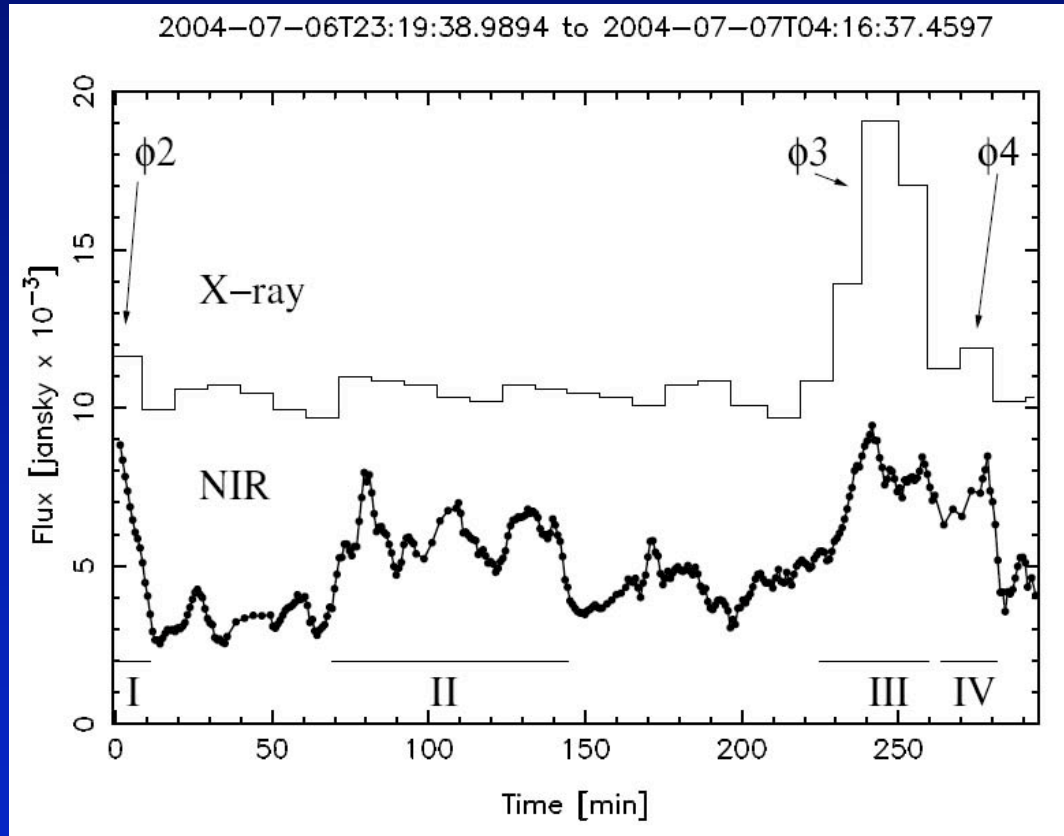


## Bayesian Blocks Analysis of July 6/7 X-ray Lightcurve



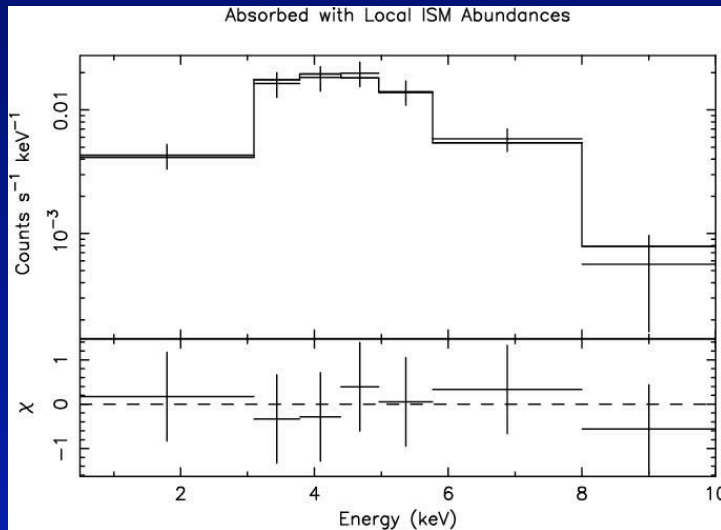
- Bayesian blocks algorithm of Scargle (1998) models the lightcurve as piecewise constant segments or blocks.
- For a discussion of the algorithm, see Eckart et al. (2004).
- Only the large flare ~18 ks into the observation is significant at the 99% CL.
- At 90% CL, a possible second event is found by the algorithm near the beginning of the observation.

# Comparison of X-ray and NIR Lightcurves

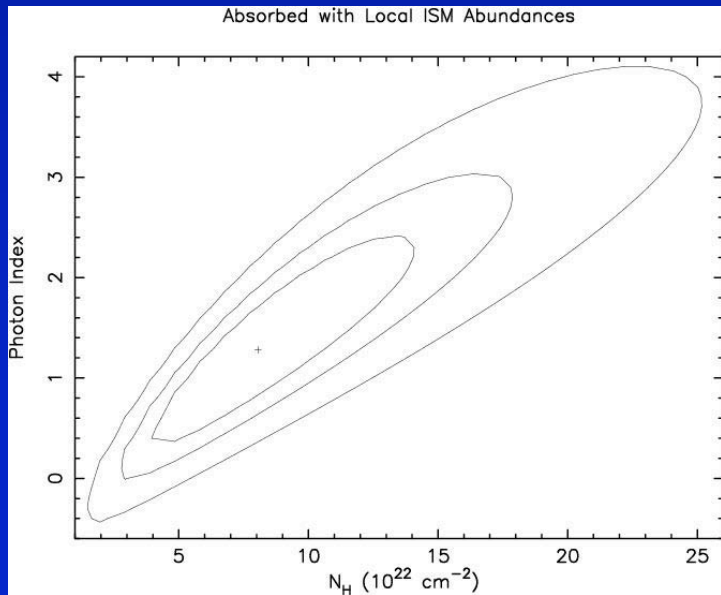


- At least four separate NIR flares were detected at K-band by the VLT with NAOS/CONICA on 2004 July 6/7.
- NIR flare III is correlated with the strong X-ray flare.
- NIR flare I is associated with the possible X-ray event at the beginning of the observations, but the ratio of X-ray to NIR amplitudes is clearly different.
- Additional strong NIR flares (II and IV) have no detected X-ray counterparts.

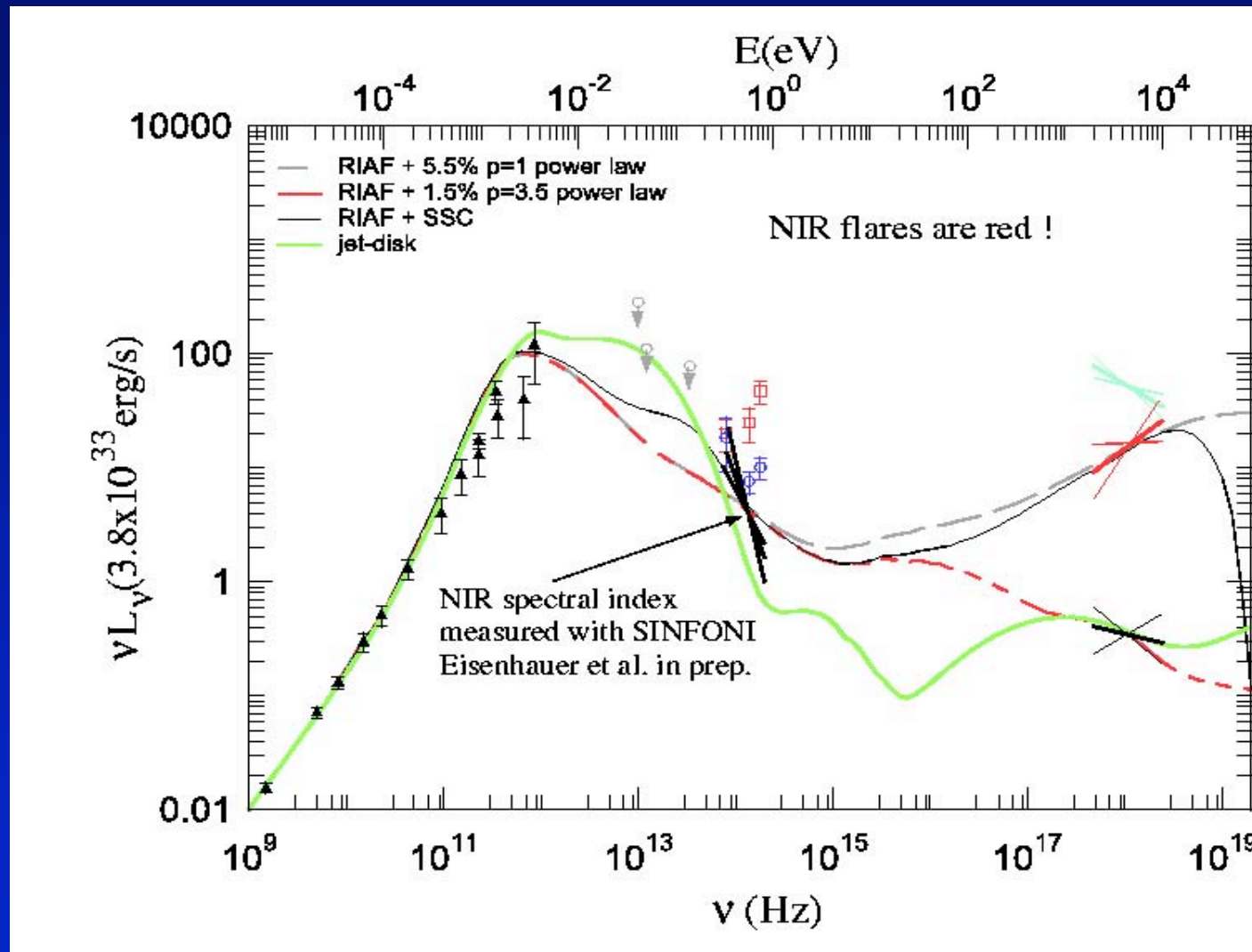
# X-ray Spectrum of July 6/7 Flare



- Model: Absorbed power law with dust scattering
- $N_{\text{H}} = 8.0 (4.0, 14.0) \times 10^{22} \text{ cm}^{-2}$
- $\Gamma = 1.3 (0.3, 2.4)$  90% CL
- Peak  $L_{\text{x}} = 3.6 \times 10^{34} \text{ erg s}^{-1}$
- Ave  $L_{\text{x}} = 3.0 \times 10^{34} \text{ erg s}^{-1}$



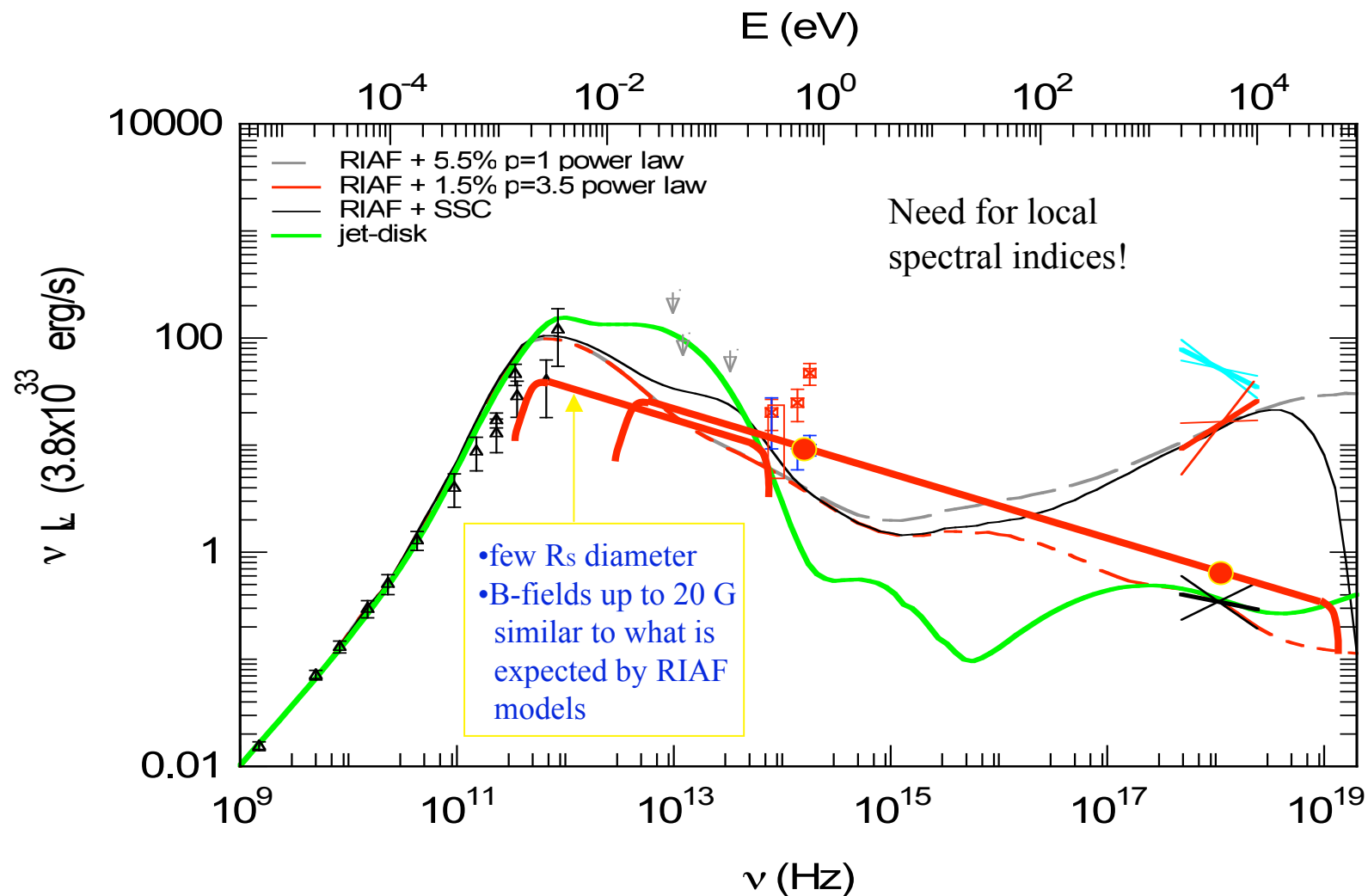
# Sgr A\* NIR Flares are Red



Implies that at least some X-ray flares must be SSC



## First Simultaneous Weak Flare and Models



Radio: Zhao, Falcke, Bower, Aitken, et al. 1999-2003

X-ray: Baganoff et al. 2001, 2003, Goldwurm et al. 2003, Porquet et al. 2003,

NIR: Genzel et al. 2003, Ghez et al. 2003

models: Markoff, Falcke, Liu, Melia, Narayan, Quataert, Yuan et al. 1999-2001

— SSC model after Marscher (1983) and Gould (1979)

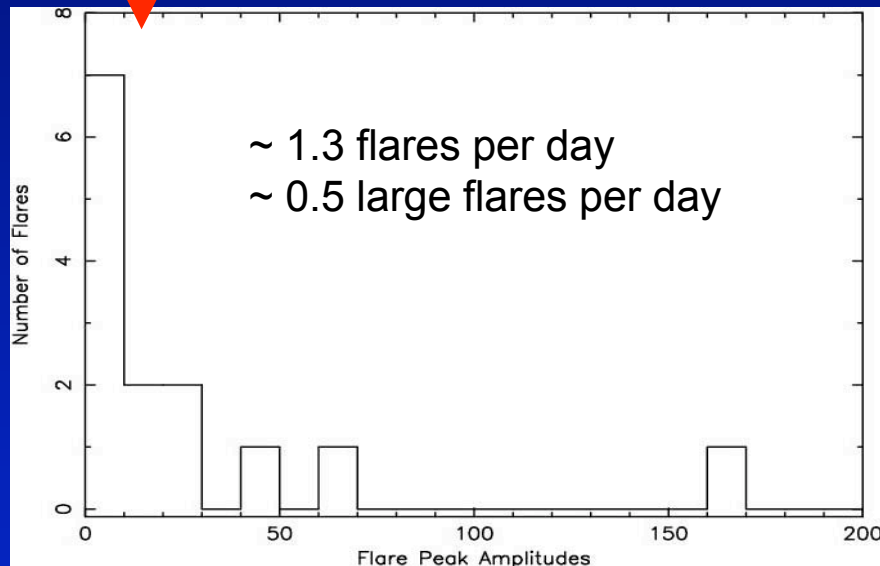
Data and model

Eckart, Baganoff, Morris et al. 2004

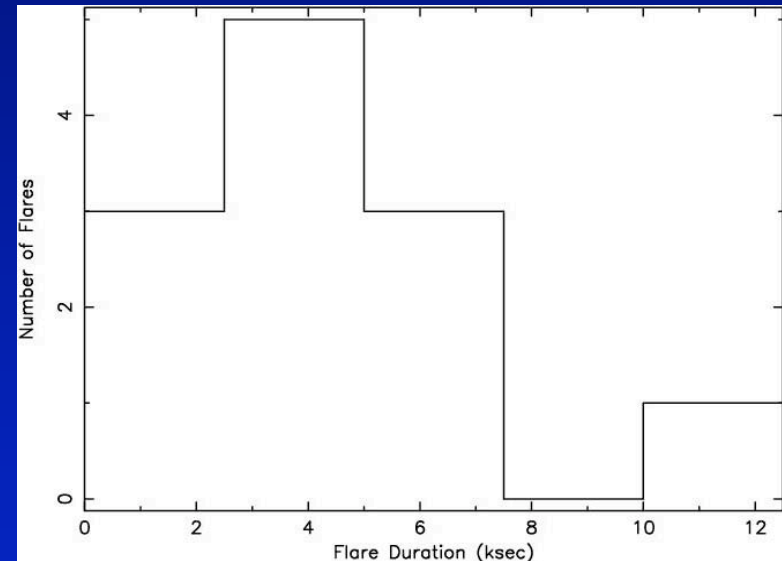
# Distributions of Flare Properties

Baganoff et al 2001, 2003; Goldwurm et al. 2003; Porquet et al. 2003; Eckart et al. 2004

Amplitudes x Quiescent Luminosity



Durations in ksec

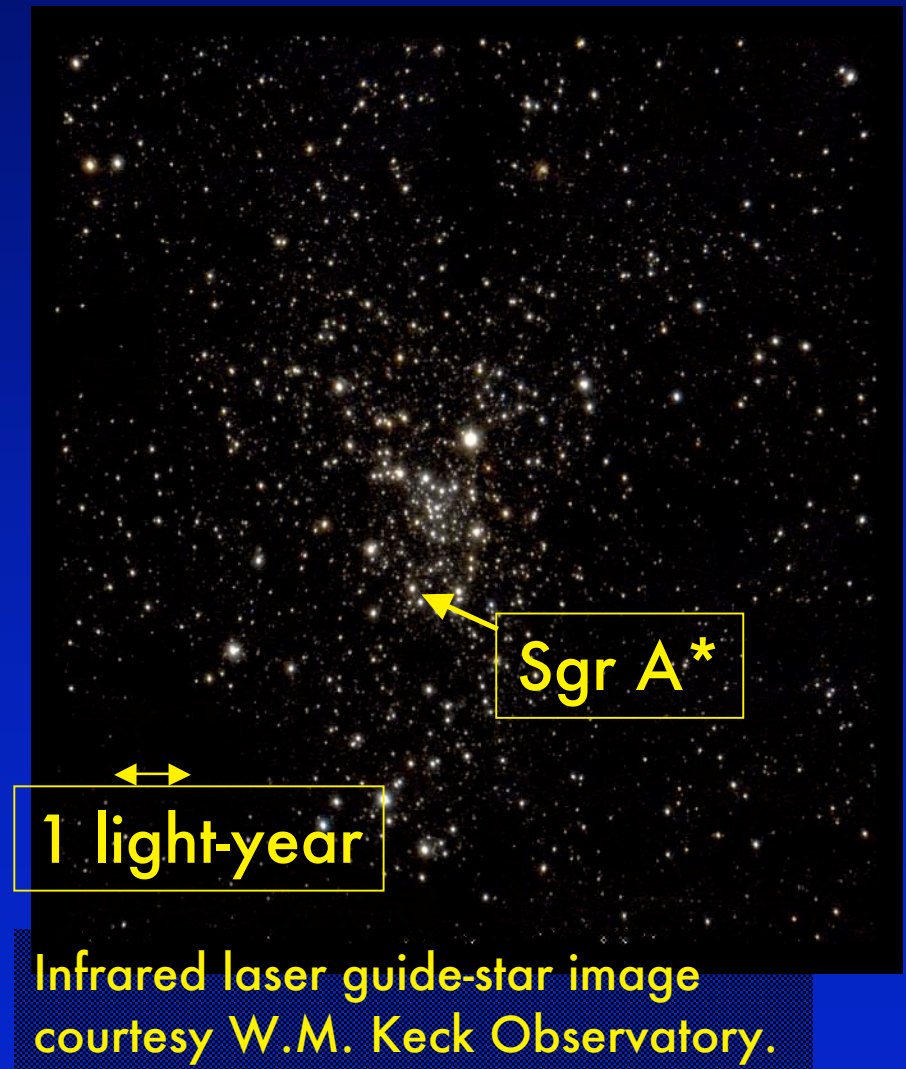


Chandra: 11 flares in 675 ks  
XMM-Newton: 2 flares in ~100 ks

Duty Cycle: 7.1 % (Chandra)

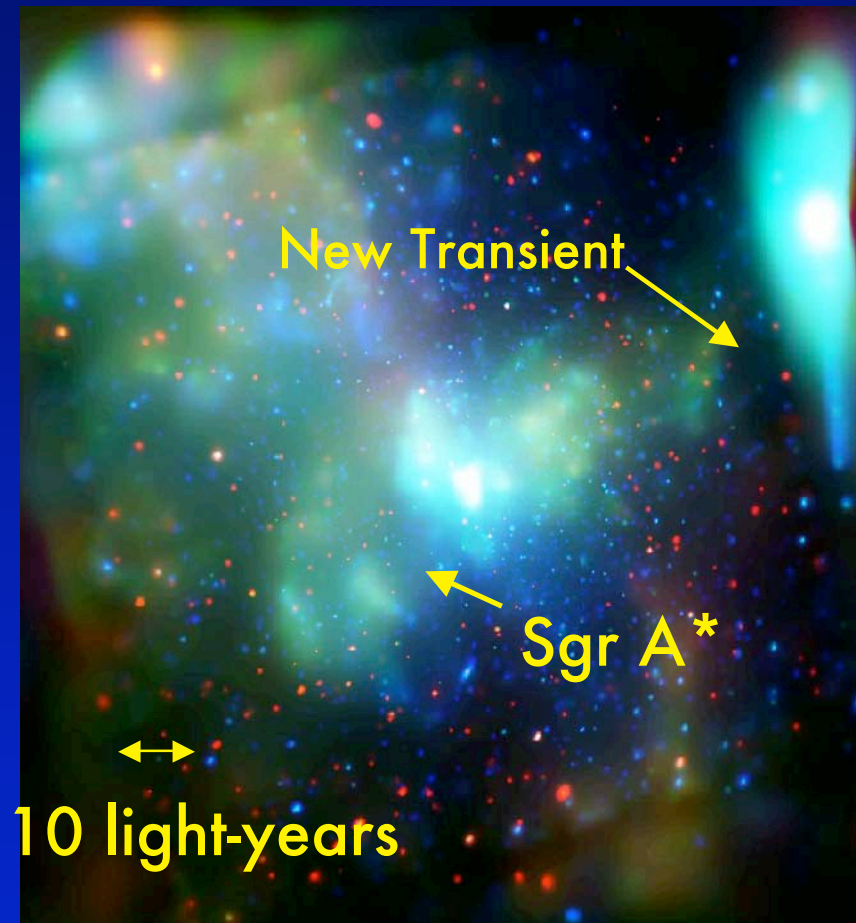
# Black Holes Settle into the Galactic Center

- In 1993, M. Morris (UCLA) predicted that massive objects -- such as black holes -- should settle toward the super-massive black hole.
- 1% of the mass in the central light-years could be black holes. (see also Miralda-Escudé & Gould 2000)



# Searching for Stellar-Mass Black Holes

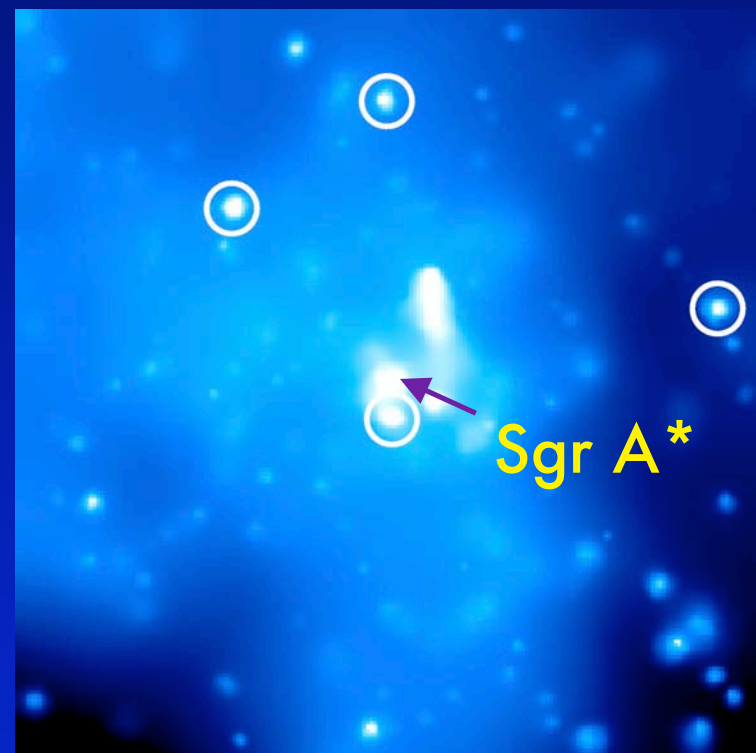
- We identified those X-ray sources most likely to be black holes and neutron stars by looking for sources that produce sudden, bright outbursts with amplitudes  $>10\times$  and peak luminosities  $> 5 \times 10^{33} \text{ erg/s}$
- We found 7 such transients within 75 light-years of the Galactic center





## An Overabundance of X-ray Binaries in the Central 3 Light-years

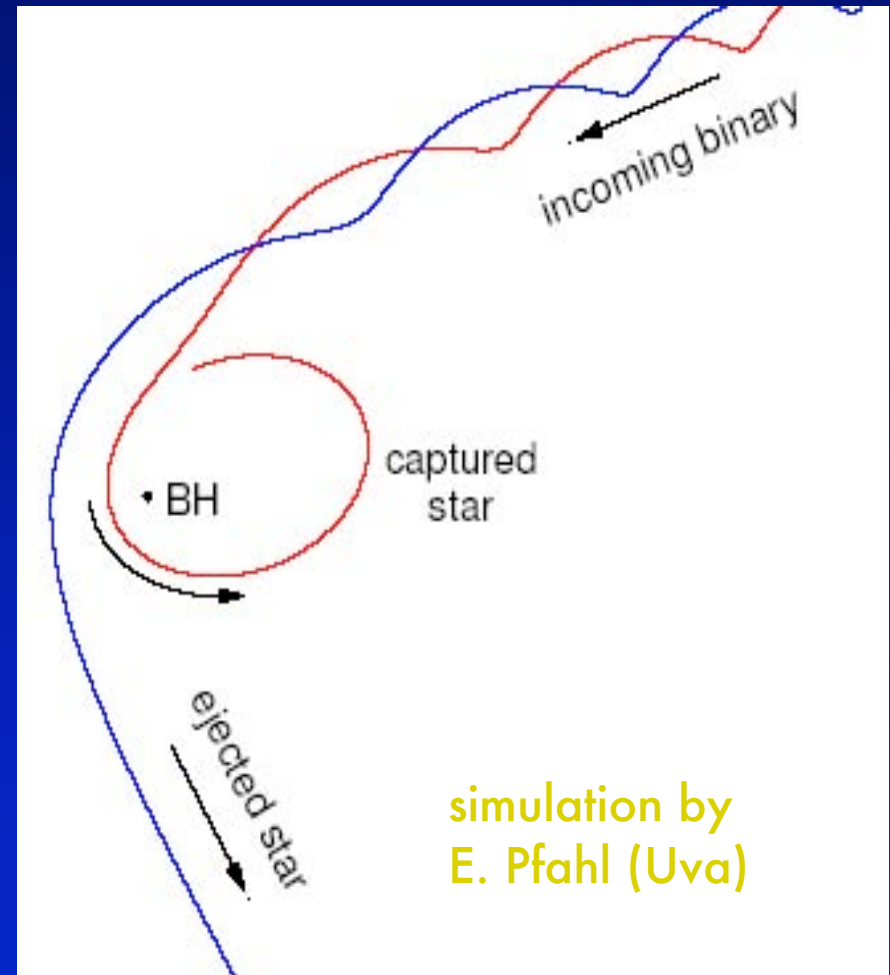
- 4 of 7 transients are within 3 light-years of the Galactic Center.
- The chance of this happening randomly is less than 1 in 5000.
- The best explanation for the overabundance is it results from a concentration of black holes and neutron stars near Sgr A\*.



1 light-year

# X-ray Binaries Form When Black Holes Capture Stars

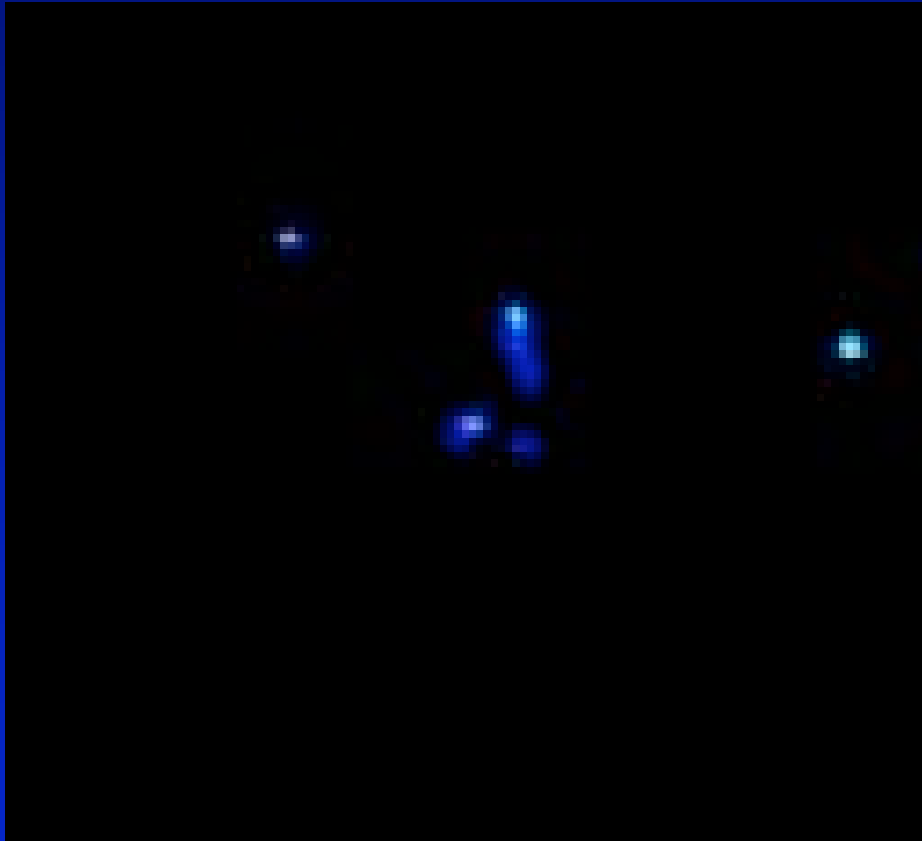
- In ten billion years, 1 in 100 black holes will encounter a binary star system, and steal one of the stars.
- A fraction of the resulting black-hole binaries will become X-ray sources.
- These X-ray binaries would be concentrated near Sgr A\*, as we see.



## Summary of X-ray Transients

- Chandra observations reveal that transient X-ray binaries are overabundant in the central 3 light-years of the Galaxy (compared to the number between 3 and 75 light-years).
- These transients are most likely accreting black holes or neutron stars.
- The overabundance can be explained if black holes and neutron stars have settled into the central light-years over the last 10 billion years.

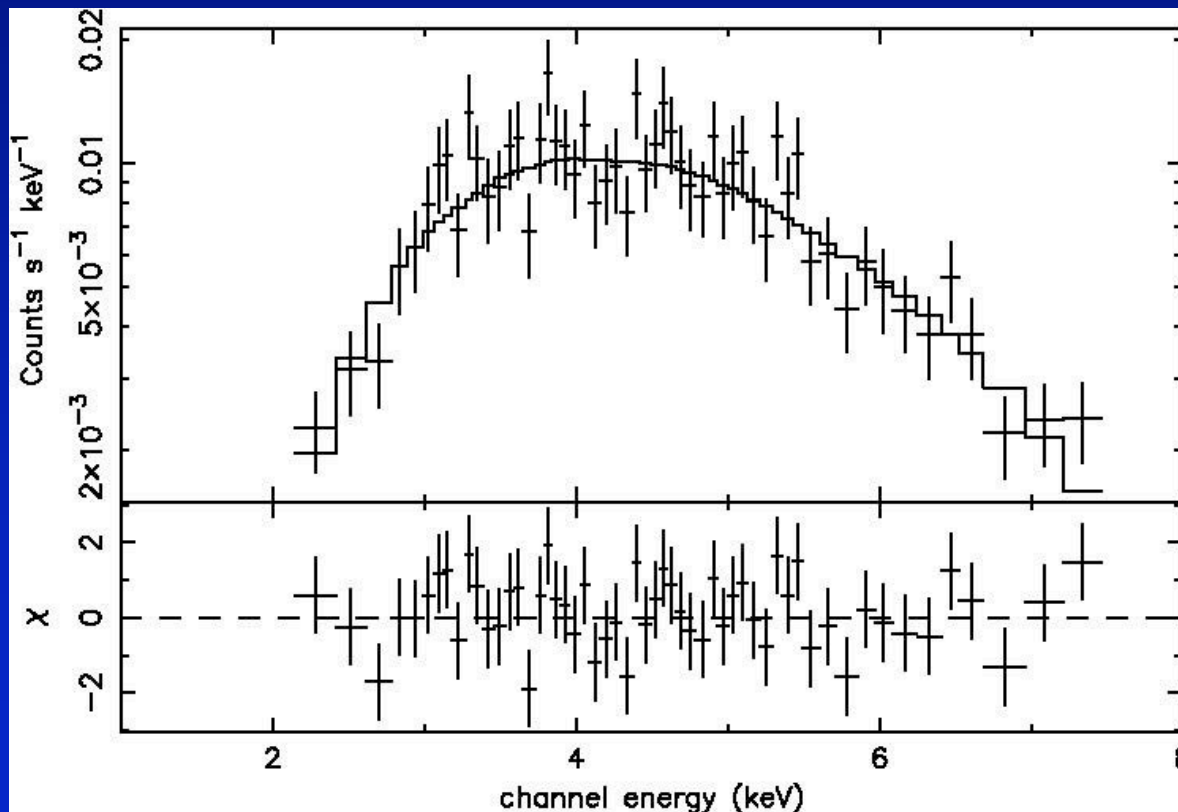
# Sgr A\* Flares and X-ray Transients in the Central Parsec of the Galaxy



- 3 hr/frame (moving avg)
- 6 days 17 hr total
- Lowest color level  $15\sigma$  above background
- Tail of PWN candidate has  $\sim 3$  ct/pix, so Poisson statistics causes apparent variability
- 7 X-ray transients detected within central 25 pc in past 5 yr
- 4 of 7 detected within central pc  $\Rightarrow 20\times$  overabundant per unit stellar mass (Muno et al. 2005)

# Integrated X-ray Spectrum of Sgr A\* During Flares

Model: Absorbed, Dust-Scattered Power Law



$$N_H = 6.0 \times 10^{22} \text{ cm}^{-2}$$
$$\Gamma = 1.3 (0.9-1.8)$$

$$F_X = 1.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$$

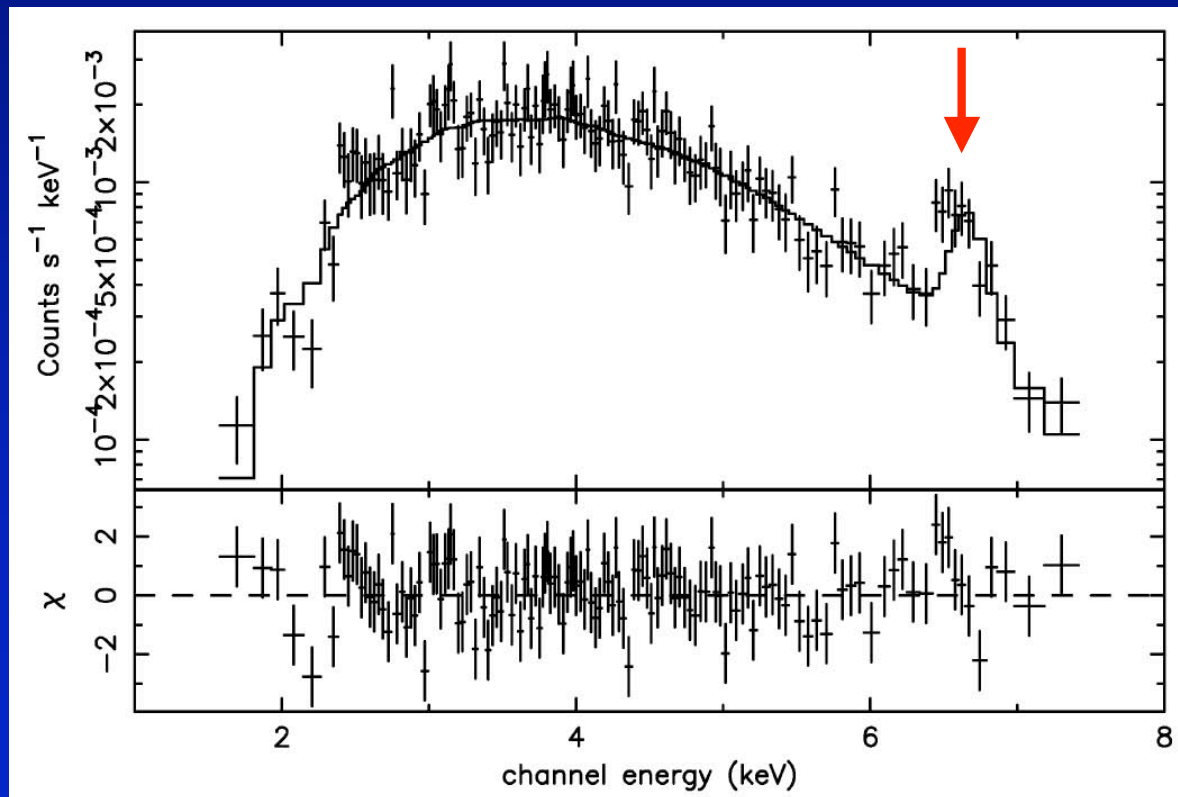
$$L_X = 2.0 \times 10^{34} \text{ erg s}^{-1}$$

$$D = 8 \text{ kpc}$$



# Integrated Quiescent X-ray Spectrum of Sgr A\*

Model: Absorbed, Dust-Scattered, MEKAL



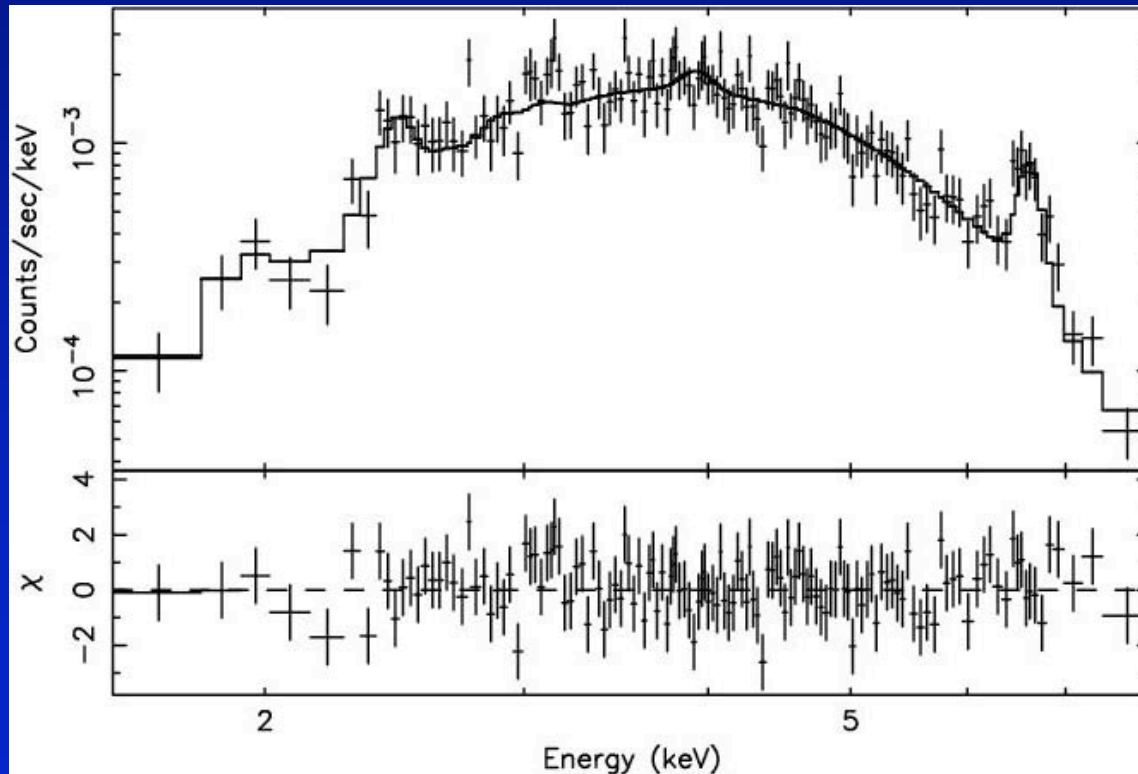
Bad fit to Fe line

Line energy too high

Abundances of light elements forced to zero

# Integrated Quiescent X-ray Spectrum of Sgr A\*

**Model: Absorbed, Dust-Scattered, NIE Plasma**



$$N_H = 5.9 \times 10^{22} \text{ cm}^{-2}$$

$$kT = 4\text{-}5 \text{ keV}$$

$$E_{\text{Fe}} = 6.59 \text{ (6.54-6.64) keV}$$

Line is narrow and NIE

$$F_X = 1.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$$

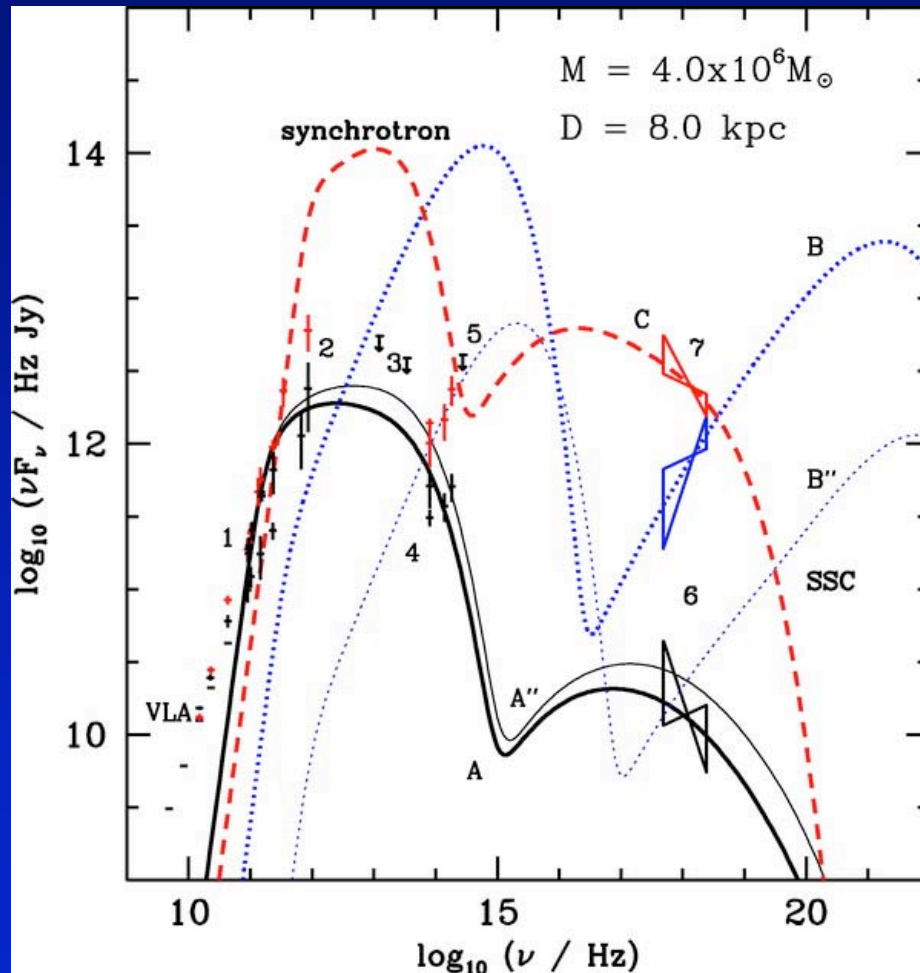
$$L_X = 1.4 \times 10^{33} \text{ erg s}^{-1}$$

$$D = 8 \text{ kpc}$$

$$\langle L_F \rangle / \langle L_Q \rangle = 14.0$$

# Stochastic Acceleration Models

Liu, Petrosian, & Melia (2004)



- Stochastic acceleration of electrons via plasma waves and turbulence as used to model solar flares
- Model A: soft quiescent spectrum; mm/IR direct synchrotron; opt/ $\gamma$ -rays SSC
- Model A': weak, soft "global" flare with  $2.5 R_S$  scale caused by increased turbulence
- Model B: strong, hard "local" flare caused by magnetic reconnection with  $0.22 R_S$  scale
- Model B': weak, hard "local" flare from  $13\times$  smaller region
- Model C: strong, soft "global" flare caused by increased  $\dot{M}$

## Summary

- Diffuse X-ray emission in central pc is due to colliding winds of stars in the central pc cluster (see Rockefeller et al. 2004, Quataert 2004)
- Discovery of an X-ray ridge 9-15" NE of Sgr A\* shows that the cluster wind is interacting with the SN ejecta of Sgr A East; hence the central pc is inside the SNR
- Chandra detected a possible X-ray jet from Sgr A\* that is oriented nearly perpendicular to the Galactic plane and that bisects the X-ray bipolar lobes
- Sgr A\* flares occur daily on average with a range of amplitudes, durations, and spectral slopes; Chandra detects flares with a duty cycle of about 7%
- X-ray and NIR monitoring in 2003 & 2004 detected two flares in both wavebands with maximum lags between wavebands of ~10 minutes

## Summary - Continued

- Steep spectral slopes of NIR flares indicate the emission process is direct synchrotron, while the X-ray emission must be SSC of submm photons from the same population of electrons (caveat: non-simultaneous obs)
- NIR and X-ray flares show a distribution of spectral slopes; stochastic acceleration models may provide a means of deriving physical properties of the emitting plasmas from the various flares
- Multiple potential sources of *GeV/TeV* emission in the central few parsecs
  - Sgr A\*
  - Sgr A East blast wave interacting with molecular gas and the central parsec cluster wind
  - Pulsar wind nebula  $\sim 0.38$  pc NE of Sgr A\*